Literature Summary to Support the Utah Lake Water Quality Study

Prepared for:
Utah Department of
Environmental Quality
Division of Water Quality

Revised: August 28, 2018

LimnoTech

Water Environment | Scientists Engineers

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El Segundo, CA

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Executive Summary

This literature review summarizes relevant background materials for the Utah Lake Water Quality Study Project, including 37 documents selected from a list of 100 previously designated as "prioritized for review", and 17 supplemental documents identified by the State of Utah after review of an initial draft of this document. The review was delivered on August 2, 2018, and presented and discussed at a meeting of the advisory Science Panel on August 8, 2018.

Documents were first categorized by topic, numbered 1-5:

1 = In-lake water quality conditions
2 = Watershed loading of nutrients to Utah Lake
3 = Internal cycling and biological availability of nutrients
4 = Ecological influences on water quality conditions in Utah Lake
5 = Influence of water management on in-lake water quality

Within topical categories, document contents were considered in light of high-level Science Panel draft charge questions, lettered a-c:

a) What was the pre-settlement and historical condition of Utah Lake with respect to nutrients and ecology?
b) What is the current state of the lake with respect to nutrients and ecology?
c) Is there a feasible improved stable state that can be reached?

Findings of the review, organized by high-level charge question, include the following:

a) Past state of the lake

- Multiple coring studies describe past sedimentology, pollen, diatoms, mollusks, and paleoenvironments; lake states based on diatoms included mesotrophic to oligotrophic conditions that were present several millennia before settlement,
- Conditions varied by location (bays vs. open lake) and were strongly linked to lake level,
- Intensive studies in the 1970s provide a good snapshot of historical conditions,
- Algal blooms are described from prior to 1970, and
- Review of historical satellite data may provide insights on prior algal blooms and other past conditions.

b) Current state of the lake

- Complex regional water budgets, including diversions, groundwater, and evaporation, are well developed,
- Fairly recent water quality data are available, especially for total dissolved solids (TDS data were used for modeling),
- Total nutrient budgets and sediment budgets exist for the lake, but there is disagreement on their sufficiency for ecological management, and on process assumptions, and
- Extensive information on lake ecology exists, particularly related to June sucker management and carp removal; algal bloom information is growing.

c) Future state of the lake

- Simulations of impacts of groundwater withdrawal and lake level modification scenarios have been conducted, but future climate change is an important unknown,
- Rapid development of the Utah Valley is likely to create additional pressure on Utah Lake water quality and ecosystems, but expected impacts are not well quantified, and
- Impacts of carp removal and nutrient loading reduction are expected to be positive, but the rates and magnitudes of related changes in Utah Lake are uncertain, and some are difficult to document.

Based on the results of this review, in order to make informed management decisions related to improvement of lake conditions, data gaps and related issues that would be important to address with quantitative research, monitoring, and modeling include the following:

- Limited age control for paleoenvironmental core studies,
- Inadequate delineation of phosphorus and nitrogen sources, speciation (e.g., particulate vs. dissolved), bioavailability, and internal cycling in the lake,
- Low resolution in time and space of loading data from tributaries and the atmosphere, as well as in-lake data on nutrients and other water-quality parameters,
- Underutilization of remote sensing as a way to quantify dynamic lake-wide conditions, despite existence of relatively mature methods,
- Understanding of linkages among food web components prioritized by management objectives, and
- Insufficient coordination and integration of planning and results from current studies via modeling and other means.

Existing extensive literature covering various aspects of Utah Lake's water quality, watershed loading, nutrient cycling, ecology, and water management provides a solid basis for formulating additional research plans. Based on this review, however, the available information appears to be insufficient to answer the Science Panel charge questions. Based on our experience answering similar questions for other systems, the most critical gaps to fill relate to incomplete understandings of nutrient budgets and sources, bioavailability, and internal cycling. This information is most critical to evaluation of management alternatives. Recent and ongoing data collection efforts that are not yet reflected in the published literature could support significant improvement in understanding, and effort to synthesize the available data deserves high priority.

Introduction and Methods

Documents Reviewed and Prioritization Process

This literature review summarizes relevant background materials for the Utah Lake Water Quality Study Project. A bibliography was provided with over 500 potential documents for review, with 100 previously designated as "prioritized for review." To make the most efficient use of project resources, LimnoTech performed a cursory review of the 100 prioritized documents provided by Utah Department of Environmental Quality (UDEQ), Division of Water Quality (DWQ) to further refine the list.

To prioritize the 100 documents, LimnoTech used several selection and sorting criteria to provide the best information to support the Science Panel in addressing high-level initial charge questions about the past, present, and future states of the lake. The final priority list was culled to 37 references, ranked as high to medium priority, according to the following:

1) Clarify documents that may have been named differently but were actually the same file.
2) Review the topics of the documents, their age, and apply best professional judgment in supporting the understanding of the water quality conditions and associated drivers of water quality within Utah Lake.
3) Documents were prioritized as 1-4.
    - 1 = high priority and most descriptive or relevant of resource
    - 2 = medium priority and resource supportive and possibly older report
    - 3 = redundant or duplicate version of another listed study (not a replicated study), or very old and not considered value added
    - 4 = not relevant or unsure of project value
4) Documents were then categorized by topic, numbered 1-5.
    - 1 = In-lake water quality conditions
    - 2 = Watershed loading of nutrients to Utah Lake
    - 3 = Internal cycling and biological availability of nutrients
    - 4 = Ecological influences on water quality conditions in Utah Lake
    - 5 = Influence of water management on in-lake water quality
5) Finally, documents were categorized based on their support of the preliminary Science Panel charge questions, lettered a-c.
    a. What was the pre-settlement and historical condition of Utah Lake with respect to nutrients and ecology?
    b. What is the current state of the lake with respect to nutrients and ecology?

c. Is there a feasible improved stable state that can be reached under the constraints of the current water management, including considerations of carp removal, nutrient reduction, and macrophyte restoration?

The publications reviewed represented a range of publication dates, including a large number from the early 1980s (especially 1981; Figures 1 and 2) that capture historical Utah Lake conditions up to the late 1970s.

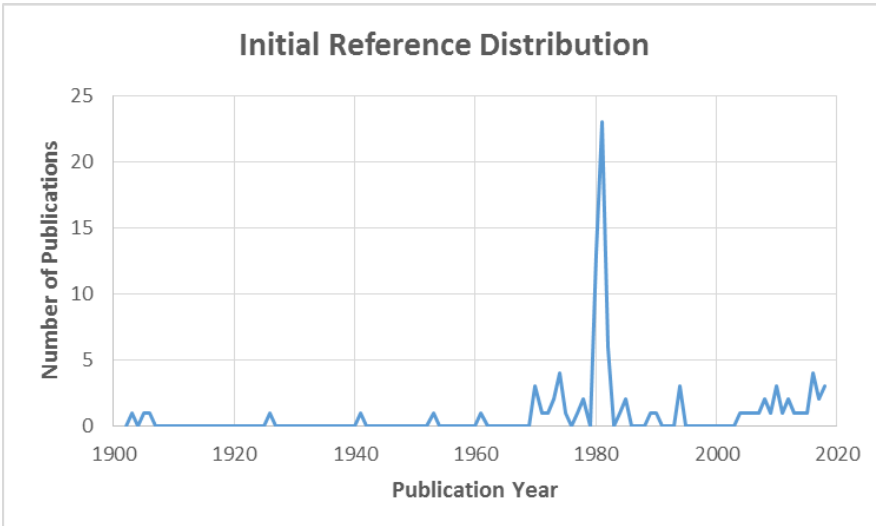

Figure 1. Number of publications in the initial review list plotted by publication year.

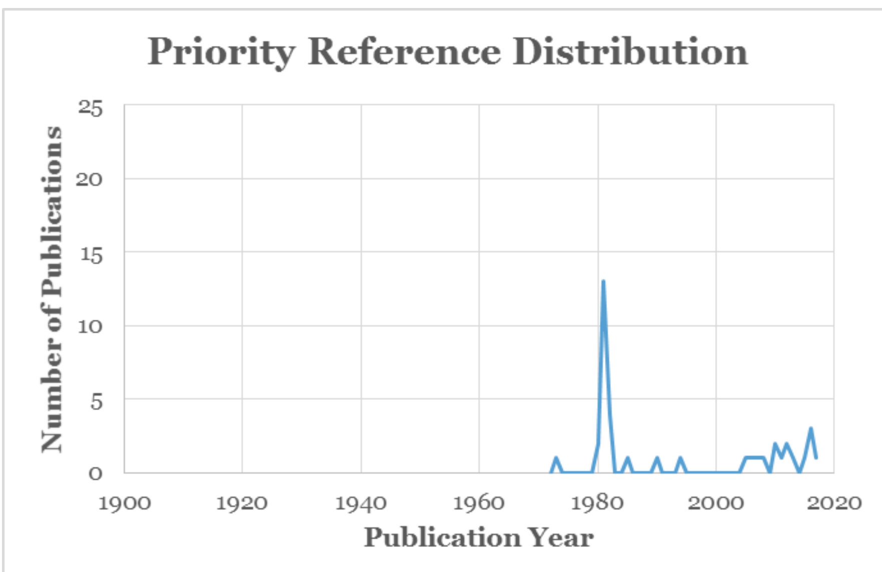

Figure 2. Number of priority references plotted by publication year.

After the initial document prioritization process, additional supplemental publications or previously lower-ranked publications were identified by DWQ staff, LimnoTech staff, Science Panel members, or through public comments, that would augment the results of the initial review. These 17 supplemental documents are listed below by topical category, and are incorporated into topical discussions of findings as appropriate for completeness, but with somewhat less detailed descriptions of their contents in some cases than documents from the initial screening. Some of these documents have been incorporated into summary tables in the appendices. They are listed below and in the "Cited References" section.

Supplemental documents

Category 1 – In-lake water quality

Bolland, R. F., 1974. Paleoecological interpretation of diatom succession in recent sediments of Utah Lake. PhD. dissertation, University of Utah.

Hansen, C. S.J Burian, P.E. Dennison, G.P. Williams. 2017. Spatiotemporal variability of lake water quality in context of remote sensing models. Remote Sensing, 9(5):409.

Javakul, A., J.A. Grimes, and S.R. Rushforth, 1980. Diatoms in Sediment Cores in Utah Lake, Utah. U.S. Bureau of Reclamation WHAB Phase One Report #16.

Rathee, G. 2017. Detection of Algal Blooms in Lakes Using Sentinal-1 C-band SAR Images. Centre for Geo-Information. Thesis Report. Wageningen University. Wageningen, The Netherlands.

Strong, A.E. 1974. Remote Sensing of Algal Blooms by Aircraft and Satellite in Lake Erie and Utah Lake. Remote Sensing of the Environment 3, p. 99-107.

Category 2 – Watershed loading of nutrients

Cassel, M.D., and R. King, 2005. Utah Lake TMDL Data Validation and Evaluation Memo, https://deq.utah.gov/legacy/programs/water-quality/watersheds/docs/2007/08Aug/UtahLake_Task1memo07-15-05.pdf

Merritt, L.B., and A.W. Miller, 2016. Interim Report on Nutrient Loadings to Utah Lake, prepared for Jordan River, Farmington Bay & Utah Lake Water Quality Council, https://le.utah.gov/interim/2017/pdf/00004081.pdf

Olsen, Jacob, 2017. Measuring and calculating current atmospheric phosphorous and nitrogen loadings on Utah Lake using field samples, laboratory methods, and statistical analysis: implication for water quality issues. M.S. thesis, Brigham Young University.

PSOMAS, 2007. Utah Lake TMDL: Pollutant Loading Assessment & Designated Beneficial Use Impairment Assessment, https://deq.utah.gov/legacy/programs/water-quality/watersheds/docs/2009/02Feb/Final_Draft_Task2_Task3_Memo%20_08-01-07.pdf

Category 3 - Internal cycling of nutrients

Abu-Hmeidan, H.Y., Williams, G.P. and Miller, A.W., 2018. Characterizing total phosphorus in current and geologic Utah Lake sediments: Implications for water quality management issues. Hydrology, 5(1):8.

Randall, 2018. Sediment potentially controls in-lake P cycling and harmful cyanobacteria in shallow, eutrophic Utah Lake.

Category 4 – Ecological influences on water quality

Crowl, T.A., and S.A. Miller, 2004. Development of macrophytes in Utah Lake: macrophyte additions and carp exclusions. 2003 Annual Report. Ecology Center, Department of Fisheries and Wildlife, Utah State University, Logan, Utah.

Richards, D.C. 2018 Relationships between Phytoplankton Richness Diversity, Zooplankton Abundance, and cyanoHAB Dominance in Utah Lake. Technical Report to Wasatch Front Water Quality Council. Research Gate.

Whiting, M. C., J. D. Brotherson, and S. R. Rushforth, 1978. Environmental interaction in summer algal communities of Utah Lake. Great Basin Naturalist.

Category 5 – Influence of water management

Brooks, L.E, 2013, Evaluation of the groundwater flow model for southern Utah and Goshen Valleys, Utah, updated to conditions through 2011, with new projections and groundwater management simulations: U.S. Geological Survey Open-File Report 2013–1171, 35 p.

Brooks, L.E., and B.J. Stolp. 1995. Hydrology and simulation of ground-water flow in Southern Utah and Goshen Valleys, Utah. Prepared by the United States Geological Survey in cooperation with the Utah Department of Natural Resources Division of Water Rights.

Cederberg, J.R., P.M., Gardner, S.A. Thiros. 2009. Hydrology of Northern Utah Valley, Utah County, Utah, 1975–2005. U.S. Geological Survey Scientific Investigations Report 2008–5197, 114 p.

Integrated Understanding of System (Findings) and Conceptual Model of Current State of the Lake

Understanding the complex processes that shape aquatic ecosystems and deriving ways to manage them sustainably while meeting human needs requires sophisticated assessments (such as numerical models) and monitoring. Conceptual models are helpful organizers of thought, information, and ideas, and represent tools for communication and inquiry among scientists, managers, and the interested public. A relatively simple conceptual model (Figure 3) for some key components within the Utah Lake system was developed to help guide the literature review and evaluation process in order to help categorize model components covered or not covered by existing literature, with the ultimate aim of describing the complex ecosystem interrelationships within the lake system.

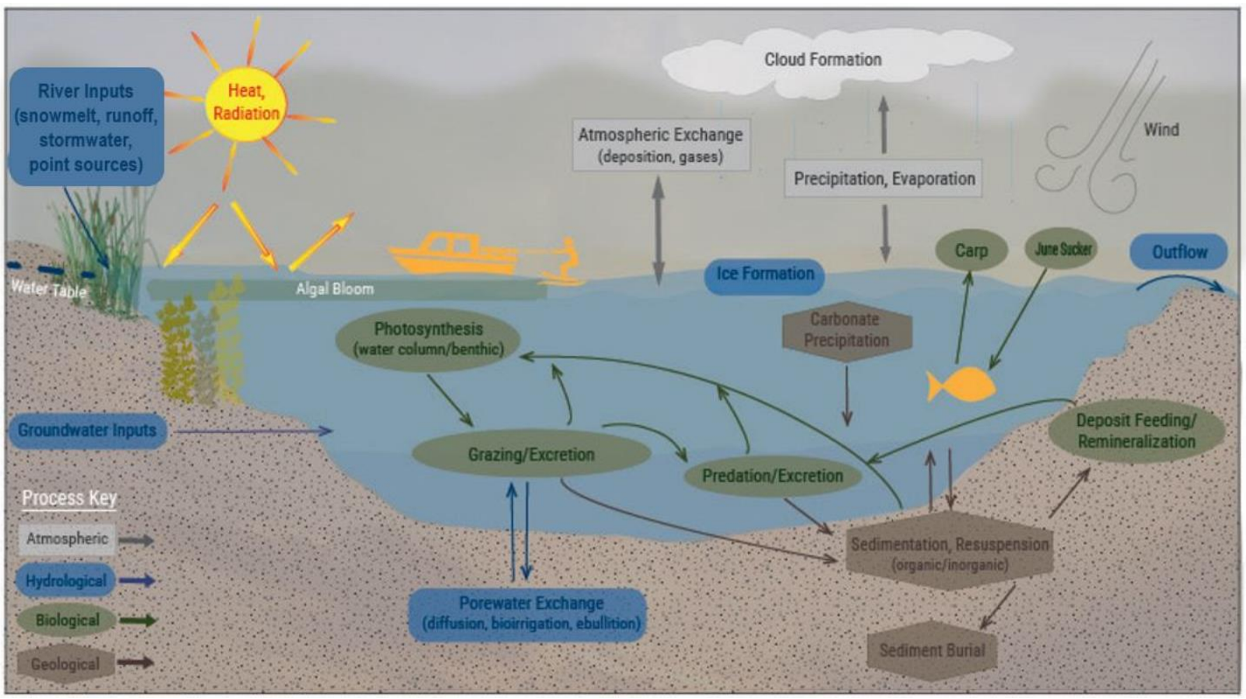

Figure 3. Conceptual model of important Utah Lake processes and phenomena.

This section lists the publications reviewed within the primary topic categories, primary findings from those publications, remaining data and information gaps, and how well reviewed publications support the Science Panel charge questions for the project. Additional details on publication categorization, relevance, and credibility are contained in Appendix A and Appendix B. It should be noted that of the 37 reports initially reviewed, several of the papers were identified on closer examination as not particularly valuable for the objectives of the project, as they were outdated, or very site-specific or project-specific, and not broadly useful for supporting Science Panel charge questions. Ongoing review of new publications, select related older publications that were not considered here, and potentially topically relevant recent publications from outside the Utah Lake basin may also be fruitful.

Topical Category 1: In-lake water quality conditions

Twelve documents were included in the priority list of documents reviewed for this category:

Barnes, J. R., D. K. Shiozawa, J. V. McArthur, and R. Y. Oberndorfer, 1982. Utah Lake phase 1 report #5: the soft-ooze benthic communities of Utah Lake Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.

Bolland, R. F., 1974. Paleoecological interpretation of diatom succession in recent sediments of Utah Lake. PhD. dissertation, University of Utah.

Bradshaw, J., Sundrud, R., White, D., Barton, J., Fuhriman, D., Loveridge, E., & Pratt, D. 1973. Chemical Response of Utah Lake to Nutrient Inflow. Journal (Water Pollution Control Federation), 45(5), 880-887.

Bushman, J.R., 1980. The Rate of Sedimentation in Utah Lake and the Use of Pollen as an Indicator of Time in Sediments.

Callister, E. V., 2008. A three-dimensional, time-dependent circulation model of Utah Lake. M. S. thesis. Utah State University, Logan, Utah.

Davis, Tiana. 2006. Quantifying Chlorophyll a Content through Remote Sensing: A Pilot Study of Utah Lake. BYU, All Theses and Dissertations. Paper 382.

Gaeta, J., R. Dillingham, and K. Landom, 2016. Utah Lake ecosystem metadata. Ecology Center and Watershed Sciences Department, Utah State University, Logan, UT.

Horns, D., 2005. Utah Lake comprehensive management plan resource document. Utah Valley State College, Orem, Utah.

Janetski, J. C., 1990. Utah Lake: its role in the prehistory of Utah Valley. Utah Historical Quarterly 58:5-31.

Javakul, A., J.A. Grimes, and S.R. Rushforth, 1980. Diatoms in Sediment Cores in Utah Lake, Utah. U.S. Bureau of Reclamation WHAB Phase One Report #16.

Macharia, A, N., 2012. Reconstruction of Paleoenvironments Using a Mass-Energy Flux Framework (Utah Lake). Doctoral dissertation. University of Utah. Salt Lake City, Utah.

Narteh, Victor Nii Afum. 2011. Mapping and Modeling Chlorophyll-*a* Concentrations in Utah Lake Using Landsat 7 ETM+ Imagery. BYU, All Theses and Dissertations. Paper 2816.

A thirteenth document was unavailable, but its findings were summarized in a separate follow-up document. This review was conducted on the relevant portions of the follow-up report. The document originally prioritized was:

Brigham Young University, 1982. Water Quality. Hydrology and Aquatic Biology of Utah Lake. WHAB Phase I Summary. Prepared for U.S. Bureau of Reclamation.

The document reviewed was:

Brigham Young University (BYU), 1982. Phase II summary report (final): Utah Lake water quality, hydrology and aquatic biology impact analysis summary for the irrigation and drainage system--Bonneville Unit, Central Utah Project. Prepared for U.S. Bureau of Reclamation.

Findings

Horns (2005) provides the most recent comprehensive description of current lake water quality-related conditions, but is more than 13 years old. The BYU (1982) report provides an even more comprehensive description of water quality, but is more than 35 years old.

Callister (2008) developed a three-dimensional hydrodynamic model of the lake, which may provide some value in describing seasonal variations in temperature and currents. It is noted that this model was calibrated using forcing functions from a combination of different time periods, such that it provides results only for a hypothetical year. This work also generated a digital bathymetric map of the lake, which may be of value to future studies.

Bushman (1980) calculated a net sedimentation rate from 1849 to 1972 of 1.38 cm per year based on the presence of dandelion pollen in sediment cores. Barnes et al (1982) compares the benthic macroinvertebrate structure for the major areas of the lake, and concludes that lower densities of oligochaetes and chironomids are found in Provo Bay than in Goshen Bay and the main lake, suggesting lower average water quality in Provo Bay.

Bolland (1974) analyzed a 5-meter piston core from NE Utah Lake, which was sampled at 250 2-cm intervals for diatoms; age horizons were correlated with prior geochemical analyses of metals, P, Na, and Ca. Settlement (1849) correlated to 300 cm. A paleoshoreline was interpreted at 470 cm based on quartz in the core. Interpretation from diatoms is that the lake has changed from a deep mesotrophic state to a shallow eutrophic state over time. Common cyanobacteria blooms were noted in a 1969 reference cited (White et al.). Mollusk lenses were present at 380-390 cm (mostly gastropods) and 450-460 cm (bivalves). Seven diatom zones were identified; notably eutrophic/alkaline zones above 372 cm, and oligotrophic/mesotrophic to "large cool lake" below; age is not well constrained, which is critical for determining sedimentation rates.

Javakul et al. (1980) related the results of an empirical study of three sediment cores from Utah Lake and Provo Bay with a focus on diatoms. The appearance of dandelion pollen was suggested as an age marker, matched with early settlement of the Utah Valley, but corresponding sedimentation rates were interpreted as too high, if linear, and age data were viewed as problematic. Diatom assemblages at different locations and core depths were described, but with little paleoenvironmental interpretation except noting of changes through time and similarities or differences among locations.

Bradshaw et al. (1973), in an older study, stated that Utah Lake received influent wastewater from nine municipalities at the time with fairly basic treatment prior to discharge. They also reported that salinity of the lake increased substantially around 1900, along with a five-foot drop in lake level. Algal blooms linked to wastewater-driven eutrophication covered all of Provo Bay and part of Utah Lake in 1969 and 1970, with associated odor and nuisance insect issues. Some material in this publication was repeated in 1981 reports by some of these authors.

Davis (2009) and later Narteh (2011), working under Prof. Mark Jackson in Geography and Prof. Brett Borup in Civil & Environmental Engineering at BYU, respectively, completed Masters theses looking at remote sensing as an approach to monitoring productivity and algal blooms in Utah Lake. Each project could be considered a pilot study or proof-of-concept, given the limited amount of in-lake sample data used to calibrate remote sensing algorithms and spectral band regressions. Davis (2009) related Landsat satellite imagery from three years in the 1990s with 27 ground-truth chlorophyll a samples from Utah Lake. Narteh (2011) showed the value of remote sensing for detecting lake-wide bloom conditions, and typical patterns of strong association of higher chlorophyll values with bays and nearshore areas along the east side of Utah Lake. This was consistent with the locations of nutrient loading sources, longer residence times of tributary inflow water, and more light penetration than in more turbid offshore waters. During summer 2005 and 2006, large open-lake blooms were detected, with similar blooms in fall of 2006. Over the time period studied, peak chlorophyll in the lake was in 2005, declining through 2010. Additional satellite proof-of-concept studies show the potential value of monitoring modern or historical algal blooms on the lake surface using Synthetic Aperture Radar (Rathee, 2017; Sentinel-1a satellite), or visible and other spectral bands (Hansen et al., 2017; Landsat, Sentinel-2, and MODIS) (Strong, 1974; ERTS MSS).

Gaps

None of the reports reviewed provide a description of water quality for the past 13 years, other than tributary TDS and ion concentration. The work in progress described by Gaeta et al (2016) will ultimately provide a more recent and comprehensive description of water quality and related conditions, but the document currently available for review represents the early phases of project work and does not provide actual data. The DWQ Phase 1 study is also in progress. Continuous water quality sondes that have been seasonally deployed in the lake since 2016 will provide valuable information on variability of water quality conditions in the lake to supplement grab sample analytical data. New atmospheric deposition data are interesting, but require more comprehensive studies to facilitate more accurate conversion to loads.

Some of the remote sensing studies use obsolete satellites that have been replaced by newer instruments with higher resolution, more extensive spectral capabilities, and more frequent repeat imaging of sites (daily versus every 10 days). Algorithms have also been developed that separate algal pigments such as chlorophyll and phycocyanin from other color-producing agents, such as suspended sediment and colored dissolved organic matter. A nationwide multi-agency project is currently underway that is developing enhanced remote sensing capabilities for algal blooms in inland lakes, including work on Utah Lake. More information on this project, known as CyAN (Cyanobacteria Assessment Network), is available here: https://www.epa.gov/water-research/cyanobacteria-assessment-network-cyan

None of the coring studies reviewed used modern age dating approaches, so the timing of changes observed in cores, and associated sedimentation rates, are somewhat speculative.

Ability to support the charge questions

Past (a)

Several of the documents reviewed provide some insight into the charge question “What was the pre-settlement condition of Utah Lake with respect to nutrients and ecology?” Macharia (2012) reconstructs historic and prehistoric environments through geochemical proxies, and concludes that disturbance at the time of establishment of agriculture and urban settlement around Utah Lake has altered nutrient and particulate matter fluxes into the lake. Janetski (1990) summarizes the work of others in describing pre-settlement conditions and the impacts settlement had on the lake, focusing on macrophytes and fish. Bushman (1980) concludes that rate of sediment deposition has increased since settlement of the Utah Valley, but there is disagreement among researchers (e.g., Bolland, 1974; Javakul et al., 1980) on sedimentation rates calculated from different cores using different dating methods, and on interpretation of paleoecological conditions in the lakes based on various core proxies.

Present (b)

Horns (2005) somewhat addresses the charge question “What is the current state of the lake with respect to nutrients and ecology?”, although data from 2005 and earlier are only marginally “current” and do not consider the large quantity of data collected since then.

Future (c)

None of the documents decisively addressed the charge question “What would be the natural nutrient regime of Utah Lake assuming no nutrient inputs from human sources?”, although several of the coring studies indicated variable states of the lake prior to human influence, with a strong influence of water level.

Topical Category 2: Watershed loading of nutrients to Utah Lake

The following seven publications were reviewed as part of the assessment of this topical area:

Cassel, M.D., and R. King, 2005. Utah Lake TMDL Data Validation and Evaluation Memo, https://deq.utah.gov/legacy/programs/water-quality/watersheds/docs/2007/08Aug/UtahLake_Task1memo07-15-05.pdf

Clark, C. W. and C. L. Appel. 1985. Ground-Water Resources of Northern Utah Valley, Utah. State of Utah Department of Natural Resources. Technical Publication No. 80.

King, R. V., and L. B. Merritt. 1981. Utah Lake Phase 1 Report #17: ground water quality along the eastern margin of Utah Lake. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.

Liljenquist, Gordon Killarney. 2012. Study of Water Quality of Utah Lake Tributaries and the Jordan River Outlet for the Calibration of the Utah Lake Water Salinity Model (LKSIM). All Theses and Dissertations. Paper 3104.

Merritt, L.B., and A.W. Miller, 2016. Interim Report on Nutrient Loadings to Utah Lake, prepared for Jordan River, Farmington Bay & Utah Lake Water Quality Council, https://le.utah.gov/interim/2017/pdf/00004081.pdf

Olsen, J.M., 2018. Measuring and Calculating Current Atmospheric Phosphorous and Nitrogen Loadings on Utah Lake Using Field Samples, Laboratory Methods, and Statistical Analysis: Implication for Water Quality Issues. All Theses and Dissertations. 6765.

PSOMAS, 2007. Utah Lake TMDL: Pollutant Loading Assessment & Designated Beneficial Use Impairment Assessment, https://deq.utah.gov/legacy/programs/water-quality/watersheds/docs/2009/02Feb/Final_Draft_Task2_Task3_Memo%20_08-01-07.pdf

Findings

Clark and Appel (1985) provide a comprehensive regional aquifer study of the Utah Lake area, including many excellent figures and examination of both the shallower and relatively low quality (elevated TDS) Pleistocene aquifers and the deeper and higher quality Tertiary aquifer. Although the study is not as focused on Utah Lake as some of the 1970s investigations, it is much more systematic and quantitative in its approach and conceptual model. More recent USGS groundwater studies in the area, which focus on management of aquifer withdrawals for agriculture and municipal supplies rather than on Utah Lake, include Brooks and Stolp (1995), Cederberg et al. (2009), and Brooks (2013); see Topical Category 5 for more discussion of these.

King and Merritt (1981), is useful as a record of prior conditions of the volume and quality of groundwater inputs into Utah Lake during the 1970s, but is of limited use in considering current or future influence of groundwater discharge on the lake.

Liljenquist (2012) collected samples of TDS and several ions from 13 tributaries, the Jordan River Outlet, and various wastewater treatment plants between 2009 and 2011, and developed regressions between concentrations of these parameters and flow. This study including no analysis of nutrients.

Cassell and King (2005) validated and evaluated Utah Lake and tributary data in support of establishment of a TMDL. They concluded that there were substantial data gaps in spatial and temporal resolution, as well as in certain parameters (e.g., algal bloom species) that limited understanding of the state and trends of the lake and its tributaries. Average Utah Lake nutrient and TDS loadings were subsequently calculated and reported in PSOMAS (2007), but temporal resolution and speciation of P and N were not adequate to capture episodic events and to determine bioavailability. The authors also state that "better characterization of the internal TP loading is central to understanding the needs of the lake."

Merritt and Miller (2016) prepared another nutrient budget for Utah Lake and concluded that "nutrient loadings are irrelevant to algae growth and water quality since: (a) These are not the limiting factors to algae growth, and cannot feasibly be reduced to growth-limiting levels, and (b) the best hypothesis is that low light availability caused by the lake's natural turbidity is the overall growth-limiting factor". While there is some evidence to support these conclusions, they do not rely on mechanistic numerical models or process experiments that constrain bioavailability of nutrients as opposed to total mass. The study reported that phosphorus loading to Utah Lake from tributaries averaged 272 tons/yr for the 2009-2013 period of study, and that the lake has a trapping efficiency of 50-90 percent.

Documents that were not reviewed in this study but which quantify tributary flows include the Utah State Water Plan, Utah Lake Basin (2014), and the Dye (2012) BYU M.S. thesis for the Central Utah Water Conservancy District on Utah Lake tributary flows.

Olsen (2018) performed an eight-month (May-Dec 2017) empirical study of atmospheric deposition of P and N at stations around Utah Lake using ground-level 5-gallon buckets, and assumed exponential decay of deposition across the lake. Total calculated loads varied widely depending on how contamination in samples (e.g., insects) was handled; between 8 to 350 tons of total phosphorus and 46 to 460 tons of dissolved inorganic nitrogen were estimated to be deposited onto the surface of Utah Lake over the eight-month sampling period. These loads, particularly the upper ends, seem unrealistically high. Better constraining results would require over-lake sampling and measurements at multiple onshore elevations, as well as atmospheric transport modeling. Locations of algal bloom initiation and greatest intensity (i.e., Provo Bay) are inconsistent with a diffuse atmospheric source as a primary driver. No attempt was made to convert calculated atmospheric loads to bioavailable fractions.

Gaps

Limited information is available in the publications reviewed on recent nutrient loading to Utah Lake. Not all statements in the older Bradshaw et al. (1973) publication or the newer Merritt and Miller (2016) report were well-supported by data; some are somewhat speculative. The approaches used to quantify nutrient loads to Utah Lake have not been particularly rigorous by comparison with other lakes and estuaries, and have not adequately constrained important processes such as atmospheric deposition or internal loading of nutrients to the lake from sediments (see Figure 3). Valuable studies, some of which are underway, would include much more extensive nutrient monitoring of multiple P and N species, and linked watershed-lake numerical modeling, such as the effort currently underway at the University of Utah (PI - Michael Barber). A related report is here: https://deq.utah.gov/legacy/destinations/u/utah-lake/docs/2016/Utah-Lake-Model-Selection.pdf

Ability to support the charge questions

Based on the publications reviewed here, there is some information available to support the charge questions; additional related information is contained in publications reviewed under other primary topical areas.

Past (a)

Natural/historical loading, apart from select snapshots in the early 1970s, will be difficult to derive, although funding of additional sediment core studies is currently being considered by groups such as the Wasatch Front Water Quality Council, which may be broadly useful in this regard.

Present (b) and Future (c)

Reports containing nutrient loading data collected since the TMDL studies in 2005 through 2007 are limited, although research projects that are currently underway have potential to inform the current state and future potential state questions.

Topical Category 3: Internal cycling and biological availability of nutrients

Four documents were included in the priority list of documents reviewed for this category:

> Abu-Hmeidan, H.Y., Williams, G.P. and Miller, A.W., 2018. Characterizing Total Phosphorus in Current and Geologic Utah Lake Sediments: Implications for Water Quality Management Issues. Hydrology, 5(1), p.8.
>
> Hogsett, M., and R. Goel, 2013. Determination of nutrient fluxes and sediment oxygen demand at selected locations in Utah Lake. Civil & Environmental Engineering, University of Utah, Prepared for: Utah Division of Environmental Quality.
>
> Merrell, P. D., 2015. Utah Lake Sediment Phosphorus Analysis. M. S. thesis. Brigham Young University. Department of Civil and Environmental Engineering.
>
> Randall, M. C. 2017. Characterizing the Fate and Mobility of Phosphorus in Utah Lake Sediments. M. S. thesis. Department of Geological Sciences. Brigham Young University.

Findings

These documents provide some insight into sediment phosphorus characteristics and fluxes, but stop short of converting bulk measurements into mobile or bioavailable fractions. Process studies are laboratory based and do not attempt to simulate actual fluxes. Hogsett and Goel (2013) report lake sediment phosphorus speciation and mineralogy, as well as sediment and water column oxygen demand. Merrell (2015) reports phosphorus and iron content of lake sediments and near-lake soils, as well as a qualitative description of phosphorus flux from lake sediments under oxic and anoxic conditions. It is noted that the results of the two studies differ in terms of reported percentage of lake sediment phosphorus that is bound to calcium.

Randall (2017) quantified lake sediment phosphorus in 26 sediment samples, with P concentrations ranging from 306 to 1894 ppm, and the highest being from Provo Bay. Results showed that ~25-50% of P is bound with calcium minerals. The study also included batch sorption experiments, which indicate that lake sediments have a capacity to absorb 70-96% of water column phosphorus over the range of 1 to 10 mg/L P.

Abu-Hmeidan et al. (2018) carried out a lake-wide sediment sampling study that showed similar P concentrations in lake sediment to those in surrounding soils (average of 666 ppm, typical range of 600-800 ppm), suggesting the importance of geological P sources to lake sediments. P hotspots were located near known anthropogenic nutrient sources (a feedlot and tributary outlets containing wastewater effluent), and areas of low P were associated with groundwater seeps. Simple lab experiments designed to show the potential mobility of P from sediments were suggestive but not conclusive. The overall conclusion that the eutrophic state of the lake was due to natural P rather than anthropogenic P was not consistent with some observed data (P hotspots), and bioavailability of P in sediments was not actually quantified—only bulk P, much of which may not be bioavailable.

Gaps

None of the studies quantify actual sediment nutrient flux rates, and no studies were available that quantified the biological availability of nutrients in lake sediments.

Ability to support the charge questions

Past (a)

These documents have limited direct value for constraining past nutrient cycling in the lake, although they could be of some use in interpreting sediment coring results, discussed under Topic 1, and in constraining total sediment P budgets.

Present (b)

The documents reviewed in this category have some value in addressing questions about the current state of the system.

Future (c)

These documents have limited direct value for constraining future states of the lake, and some actually overstate conclusions in this regard.

Topical Category 4: Ecological influences on water quality conditions in Utah Lake

Fourteen documents were included in the priority list of documents reviewed for this category:

Barnes, J. R., D. K. Shiozawa, J. V. McArthur, and R. Y. Oberndorfer. 1981. Utah Lake phase 1 report #2: winter zooplankton communities of Goshen Bay Utah Lake, Utah, USA. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.

Barnes, J. R., D. K. Shiozawa, J. V. McArthur, and R. Y. Oberndorfer. 1981. Utah Lake phase 1 report #3 and #8 combined: Utah Lake littoral community analysis: October 1978–May 1979. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.

Barnes, J. R., D. K. Shiozawa, J. V. McArthur, and R. Y. Oberndorfer. 1981. Utah Lake phase 1 report #7: Utah Lake littoral community analysis: Intensive site zooplankton studies Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.

Barnes, J. R., D. K. Shiozawa, R. Y. Oberndorfer, and J. V. McArthur. 1981. Utah Lake phase 1 report #6: Utah Lake littoral benthic community: an intensive study. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.

Barnes, J.R. and Toole, T.W. 1981. Macroinvertebrate and zooplankton communities of Utah Lake: a review of the literature," *Great Basin Naturalist Memoirs*: Vol. 5, Article 7.

Brotherson, J.D. 1981. Aquatic and semiaquatic vegetation of Utah Lake and its bays. *Great Basin Naturalist Memoirs*: Vol. 5, Article 5.

Crowl, T.A. and S.A. Miller. 2004. Development of macrophytes in Utah Lake. Macrophyte additions and carp exclusions. Annual report submitted to Utah Department of Natural Resources. Project Number V.02.09. Ecology Center, Utah State University, Logan, Utah.

Heckmann, Richard A.; Tompson, Charles W.; and White, David A. 1981. Fishes of Utah Lake, *Great Basin Naturalist Memoirs*: Vol. 5, Article 8.

Landom, K. 2010. Utah Lake food web part I – Introduced sport fish and fish conservation in a novel food web: evidence of predatory impact. Final report submitted to the June Sucker Recovery Implementation Program. Ecology Center, Utah State University, Logan, Utah.

Landom, K., C. J. Keleher, S. Rivera, and T. A. Crowl. 2014. Coupled ecosystem monitoring and biomanipulation in the shallow, eutrophic, Utah Lake. Final report to the June Sucker Recovery Implementation Program, Ecology Center and Watershed Sciences Department, Utah State University, Logan, Utah.

Landom, K., T. A. Crowl, P. Budy, G. P. Thiede, and C. Luecke. 2010. Utah Lake food web part II – Biomanipulation and fish conservation in the shallow, eutrophic, Utah Lake: a combined bottom-up and top-down food web modeling approach. Final report submitted to the June Sucker Recovery Implementation Program. Ecology Center, Utah State University, Logan, Utah.

Richards, D. C. and T. Miller. 2017. A preliminary analysis of Utah Lake's unique foodweb with a focus on the role of nutrients, phytoplankton, zooplankton, and benthic invertebrates on HABs. Utah Lake Research 2016. Progress Report. Wasatch Front Water Quality Council, Salt Lake City, UT.

Richards, D.C. 2018 Relationships between Phytoplankton Richness Diversity, Zooplankton Abundance, and cyanoHAB Dominance in Utah Lake. Technical Report to Wasatch Front Water Quality Council. Research Gate.

Whiting, M. C., J. D. Brotherson, and S. R. Rushforth, 1978. Environmental interaction in summer algal communities of Utah Lake. Great Basin Naturalist.

Findings

Of the reviewed priority documents, the Utah Lake Phase 1 (Barnes et al. 1981; and Barnes and Toole 1981) reports provided detailed condition and taxonomic description of the benthic macroinvertebrate, zooplankton, and substrate conditions in the late 1970s. The Phase 1 reports also described the overall differences in the communities among main lake, Goshen Bay and Provo Bay, with the bay areas containing a greater diversity in community structure and abundance. Unfortunately the reports provided little or no discussion about the relationship between biotic condition and the water quality conditions within the lake or bay areas at that time.

Brotherson (1981) provided a thorough description of aquatic and semiaquatic plant communities around the main lake and its major bays. The study offers detailed descriptions taken from literature (pre-1974) and supplemented with field surveys in 1976. Plant community types identified and quantified across the lake included density characteristics representing the publication period (late 1970's). The early settlement period is also characterized. Although specific measures of plant community effects on water quality (e.g., DO, nutrients, biomass, phytoplankton, BOD, etc.) aren't included in the paper, it may offer background and a snapshot in time for water quality model support.

Crowl and Miller (2004) evaluated the direct and indirect effects of carp on water quality, invertebrates and macrophytes within Utah Lake. The in-situ studies included small and large scale evaluations. The studies, conducted in 2002 and 2003, provided a relevant assessment of direct and indirect disturbance effects on submergent and emergent macrophytes at two locations in the lake – Provo and Saratoga. The report also describes macrophyte restoration recommendations based on carp exclusion studies, as well as macrophyte consumption preference, and provides valuable, lake-specific observations and insight into post-carp impacts on the macrophytes, as well as considerations for macrophyte restoration.

Heckmann et al. (1981) offers an important, historic description of the Utah Lake fisheries resources and its developments pre-settlement to mid 1970's period. This report includes a detailed, although qualitative, historical description of the native and introduced species and their community changes through time. The report provides a valuable timeline of transitions in lake management, development, discharges, inflow controls and fisheries management and harvest. The report provides a valuable resource describing changes at the species and community level as water quantity and quality have changed over time.

Landom (2010) reports on components of a lake-wide food web model for Utah Lake with the intent to understand how the introduced species and size classes affect native fish reproduction and survival within the lake. The report uses stable isotopes (SI), quantified diet, and SI mass balance models to quantify trophic interactions. The report offers detailed descriptions of the methods, materials and results from the data collections from 2006-2007. Three food web models are presented and compared: stable isotope-derived food web, a quantified diet-derived food web, and finally, an integrated stable isotope and quantified diet food web. The report appears to provide support for model parameterization for Utah Lake.

Landom et al. (2010) reports a second phase of analysis based on Landom (2010) using a food web model approach to understand 1) food web responses to removal of carp and white bass, 2) fish predator impacts on June sucker and juvenile carp, 3) the re-establishment of a prey species (Utah chub). The study includes a detailed description of the methods, results and conclusions along with management scenario findings resulting from the model runs. The report presents important, relatively recent, lake-wide top-down, bottom-up food web modeling, providing valuable descriptions of manipulation responses under fish management scenarios. The report provides information gaps and management recommendations.

Landom et al. (2014) reports on the planning and design of a long-term monitoring program for several Utah Lake ecosystem components, using an ecosystem conceptual model (Figure 4) as a guide. Elements included (1) water quality: total phosphate, turbidity, total suspended solids, total dissolved solids, and secchi depth, (2) phytoplankton: chlorophyll a, cyanophyta density, and chlorophyta density, (3) zooplankton: large taxa biomass, small taxa biomass, large taxa body size, and small taxa body size, (4) macroinvertebrates: overall biomass and overall abundance, (5) fisheries: carp abundance, sport fish abundance, carp biomass, and sport fish biomass, (6) and macrophytes: percent of lake coverage by taxa. The approach appears to provide valuable and applicable components necessary for building and maintaining a broadly useful ecosystem model. Along with sampling and data quality recommendations, the report includes recommendations for data analysis for a model to better describe ecological relationships, change and causality.

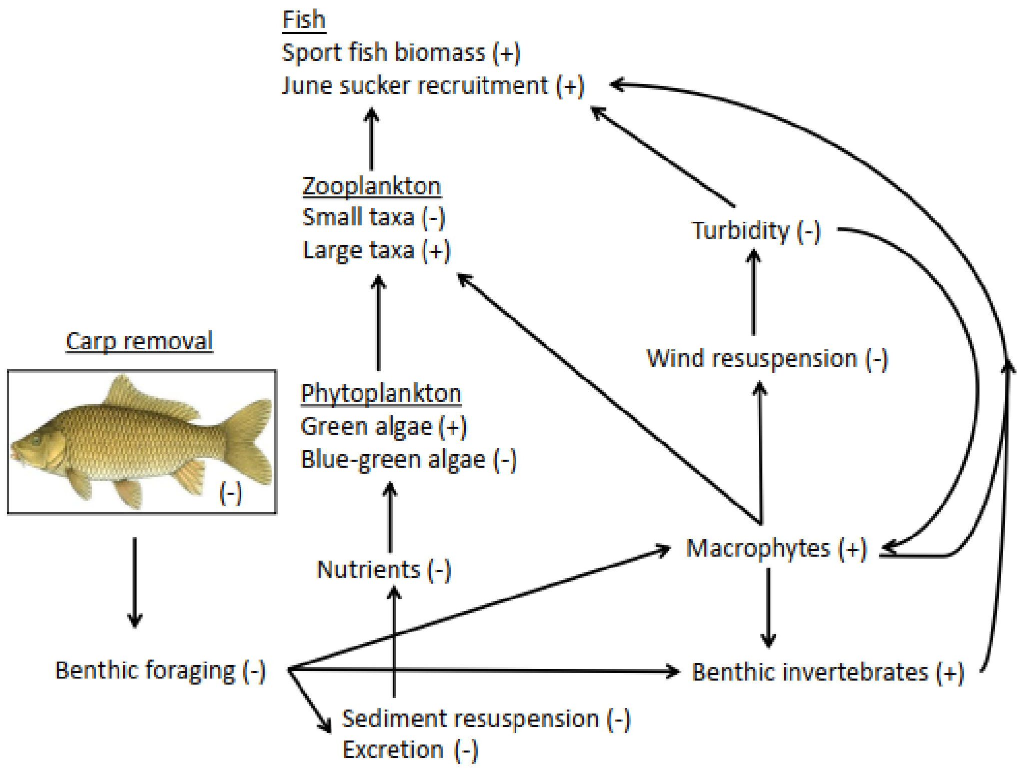

Figure 4. Simple conceptual model of the Utah Lake food web and associated responses from carp removal. Landom et al. (2014)

Richards and Miller (2017) provide a recent and detailed assessment of Utah Lake phytoplankton, zooplankton and benthic macroinvertebrate communities to understand the lake food web dynamics. The study includes conceptual as well as numerical models depicting several key food web relationships (Figures 5 and 6). The phytoplankton, zooplankton and macroinvertebrate components of this study provide a useful characterization of features necessary for modeling the role and sources of nutrient conditions and flux across Utah Lake, with the intent of using this information to understand the cyanobacteria-composed, harmful algal blooms (HABs). The report also includes updated, foundational data on taxonomic characterizations and methods and results of the analysis of the survey data across 2016, valuable for several components of a water quality model.

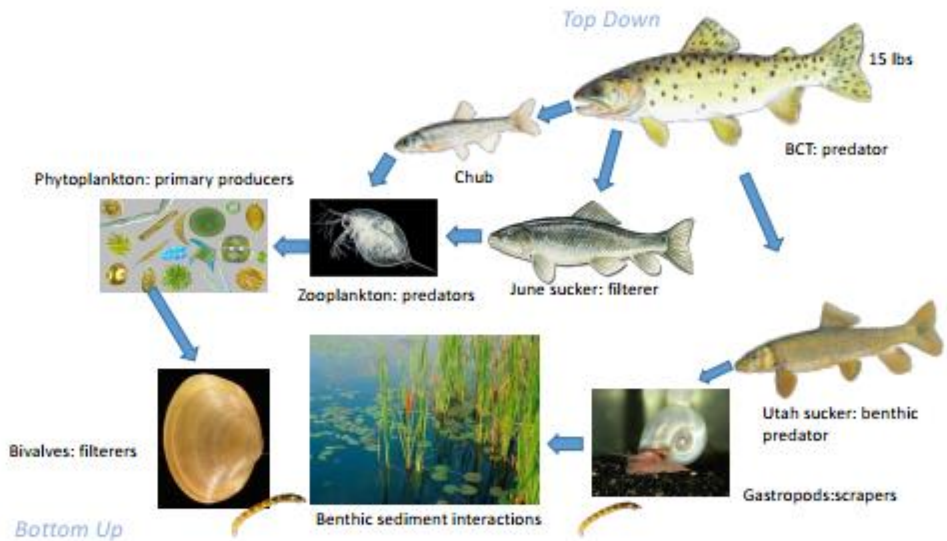

Figure 5. Simple conceptual model of pre-1890 Utah Lake food web (Richards and Miller 2017)

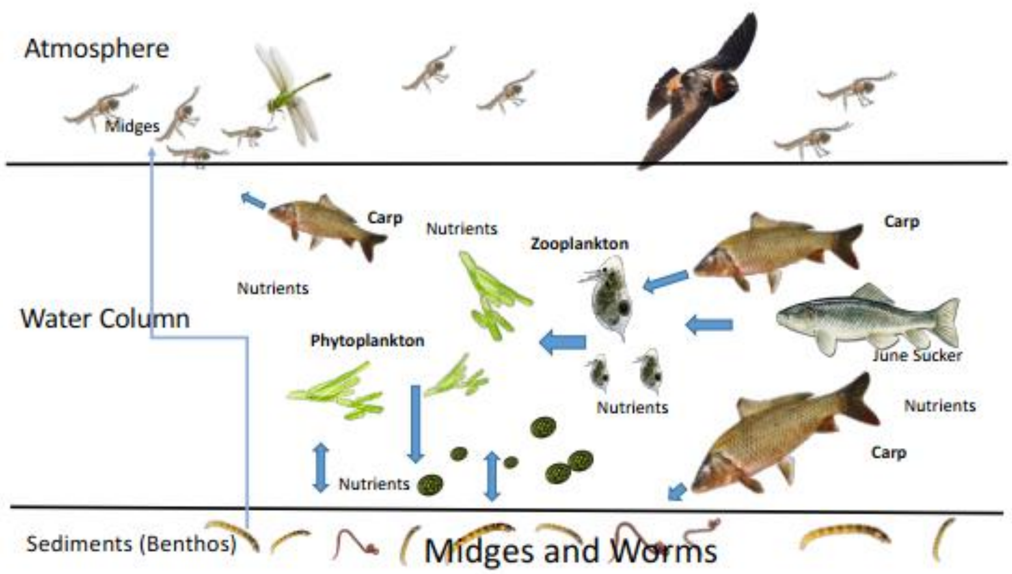

Figure 6. Simple conceptual model, circa 2016, of the Utah Lake food web (Richards and Miller 2017)

Richards (2018) used statistical analyses of 133-135 samples to test five hypotheses: 1) Spatial and temporal factors affect phytoplankton richness, diversity, similarity, and abundance; 2) Phytoplankton abundance affects phytoplankton richness, diversity, and similarity; 3) Zooplankton abundance affects phytoplankton richness, diversity, similarity, and abundance; 4) Zooplankton abundance is affected by phytoplankton richness, diversity, similarity, abundance, and spatial and temporal factors.; and 5) cyanoHABs have more of an effect on phytoplankton taxa richness than do diatom or green algal blooms. Preliminary results indicate that: 1) Utah Lake's unique phytoplankton assemblages are both spatially and temporally dynamic and resilient to blooms; 2) when cyanoHABs were most abundant, phytoplankton taxa richness appeared to decline, however dominance by cyanoHABs did not affect phytoplankton taxa richness any more than did diatom or green-algal blooms, nor did they appear to cause extinction of phytoplankton taxa; and 3) phytoplankton richness was affected by zooplankton abundance and vice versa.

Whiting et al. (1978) describes algal community changes across the summer season of 1974 along three cross-lake transects. They found a low standing crop but rich species diversity early summer, an increased standing crop associated with green algae declines in mid-summer, and late summer conditions of low species diversity but the highest standing crop. Species diversity declines seemed to be correlated with decreased inorganic carbon in late summer. The authors note that declining carbon limits are likely an important factor driving competitive exclusion in the summer phytoplankton communities in Utah Lake.

Gaps

The following are data gaps identified in the reports, during the review of the papers for the Ecological Influences category. The gaps identified below summarize the report recommendations with consideration of the overall significance of the gaps in light of the full set of publications reviewed for the Ecological Influences category, and the objectives of this review project.

Barnes et al. (1981; Phase 1 Report 2) suggested winter sampling of zooplankton removes the important influence of wind on depicting regional conditions within and across the lake. Consider the relative and practical importance of collecting and characterizing zooplankton communities in the main lake and Provo Bay areas during winter periods to better depict the local, minimum, standing stock conditions and better understand grazing impacts on phytoplankton.

Barnes et al. (1981; Phase 1 Reports 3&8) describe the importance and influence of lake location (i.e., wave action; lake bottom gradient and water quality) and substratum (i.e., embeddedness, interstitial flow, stability, attachment sites and substrate permeability) on macroinvertebrates. Consider the importance of modeling the effect of restoring the density and distribution of the macrophyte communities on macroinvertebrate and early life stage fish communities in the main lake.

Barnes and Toole (1981) suggested improving the understanding of grazing impacts of zooplankton on phytoplankton within and across Utah Lake.

Crowl and Miller (2004) suggested additional evaluations on macrophyte growth and recovery in the presences of both carp density impacts as well as wind and, associated wave actions effect key areas of the lake. Consideration of native species types that are more resilient to wind and wave action should be examined further. Further, better understanding of carp biomass and densities and trends and preferences in habitat use across the lake may provide insight into locations and conditions that may be more suitable for macrophyte restoration. For example, Potomegoton beds at Saratoga may offer better macrophyte success and valuable for June sucker larvae.

Under the increased commercial harvest of carp, how and where has the aquatic and semiaquatic macrophyte community responded to decreased disturbance compared to previous conditions like those described in Brotherson (1981)? (This is currently being studied by Jereme Gaeta of Utah State University.)

Richards and Miller (2017) suggest the need to better understand the strong relationship between midge biomass and cyanobacteria blooms. That is, does midge biomass regulate phytoplankton intensely enough to suppress cyanobacteria production?

Richards (2018) provided preliminary analysis of phytoplankton and zooplankton assemblages with a detailed analysis of their data, results, and recommendations pending.

Landom (2010) suggests a need to better characterize the organizational structure of the Utah Lake food web during low water years (drought conditions and/or anthropogenic driven).

Landom et al. (2010) suggests the need to better understand how/if the reestablishment of macrophytes would affect predator-prey dynamics of the fisheries community.

Landom et al. (2010) suggests reevaluating the reproduction and survival potential of Utah chub as an introduced forage species, given the pressure from introduced piscivores.

Landom et al. (2010) states that fish population abundance data is lacking to support a better understanding of trophic interactions within the lake.

Landom et al. (2010) describes the need for improved abundance data for Utah Lake sucker populations, larval sucker production, and predator abundance (particularly white bass) to support lake, bioenergetics modeling efforts.

Landom et al. (2014) recommends establishing a standardized, annual sampling program that includes five main components to support ecosystem monitoring and modeling efforts - 1) pelagic water quality, phytoplankton, and zooplankton, 2) littoral zooplankton sampling, 3) littoral macroinvertebrates sampling, 4) carp and sportfish monitoring, 5) emergent vegetation monitoring.

Whiting et al. (1978) suggests the need to better understand inorganic carbon limits on green algae composition and abundance.

Ability to support the charge questions

Past (a)

Pre-settlement conditions were best described for fisheries and macrophyte resources, but poorly for other components of the food web.

Present (b)

The reviewed literature for the Ecological Influences category best supported the charge questions related to the current state of the lake ecology.

Future (c)

An improved stable state under the current water management conditions is challenging to assess for the ecological resources. Top down pressures of predatory fishes on the food web appear difficult to quantify, yet are heavily influencing ecosystem components. Carp removal may improve macrophyte density and distributions, but the effects on nutrients was not discussed in the papers reviewed. None of the reviewed papers discussed ecosystem responses from nutrient reductions.

Topical Category 5: Influence of water management on in-lake water quality

The following 10 publications were reviewed as part of the assessment of this topical area:

Ashcroft, W., and L. B. Merritt. 1980. Utah Lake phase I report #1: quantity and quality of Goshen Bay inflows. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.

Brooks, L.E, 2013, Evaluation of the groundwater flow model for southern Utah and Goshen Valleys, Utah, updated to conditions through 2011, with new projections and groundwater management simulations: U.S. Geological Survey Open-File Report 2013–1171, 35 p.

Brooks, L.E., and B.J. Stolp. 1995. Hydrology and simulation of ground-water flow in Southern Utah and Goshen Valleys, Utah. Prepared by the United States Geological Survey in cooperation with the Utah Department of Natural Resources Division of Water Rights.

Cederberg, J.R., P.M., Gardner, S.A. Thiros. 2009. Hydrology of Northern Utah Valley, Utah County, Utah, 1975–2005. U.S. Geological Survey Scientific Investigations Report 2008–5197, 114 p.

CUWCD. 2007. Utah Lake water level fluctuation. Final report to the June Sucker Recovery Implementation Program. Central Utah Water Conservancy District, Orem, Utah.

Fuhriman, Dean K., Merritt, Lavere B., Miller, A. Woodruff, and Stock, Harold S. 1981. Hydrology and water quality of Utah Lake. Great Basin Naturalist Memoirs: Vol. 5, Article 4.

Brimhall, Willis H. and Merritt, Lavere B. 1981. Geology of Utah Lake: implications for resource management. Great Basin Naturalist Memoirs: Vol. 5, Article 3.

Fuhriman, D. K., and L. B. Merritt. 1981. Utah Lake Phase 1 Report #12, Utah Lake surface inflows and outflows: 1930-1980. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.

Holden, P. B., C. N. Goodwin, and K. D. Thesis. 1994. A study to determine appropriate water management actions to enhance native and sportfish populations in Utah Lake: summary of existing information and preliminary feasibility study. BIO/WEST, Inc., Logan, Utah.

Gaeta, J., and K. Landom. 2016. A whole-ecosystem response of a shallow lake to drought and an invasive carp removal, with an emphasis on endangered fish conservation. Utah State University, Ecology Center and Department of Watershed Sciences.

Findings

Several of the older studies reviewed here, including Ashcroft and Merritt (1980), Fuhriman et al. (1981), Brimhall and Merritt (1981), and Fuhriman and Merritt (1981), and King and Merritt (1981), are useful as snapshots of prior conditions of flow and water quality in Utah Lake during the 1970s, but are of limited use in considering current or future states of the lake, given subsequent changes in watershed infrastructure, development, and loading. Several of these studies provide overlapping information, and discussions of topics and hypotheses that relate to the data presented in the publications, but which are not always directly supported by those data. One example would be statements regarding nitrogen as the limiting nutrient in the lake, with limited data or citations to support these statements. The Liljenquist (2012) thesis updates the approach used in many of these papers.

One of these older publications that is particularly relevant regarding historical and recent conditions in the lake is Brimhall and Merritt (1981). The publication describes a 520-cm sediment core from Utah Lake (see also sediment coring studies reviewed under Topical Category 1), along with surface sediment analyses from 140 stations. No direct age control (e.g., radioisotopes or pollen) was reported for the sediment core, but estimation of sedimentation rates based on assignment of a subsurface seismic reflector as corresponding to the last Lake Bonneville deposits yielded linear sedimentation rates of 0.8 to 1.5 mm/yr. Peat/sand at 450-cm depth in the core was assigned to the altithermal period (very arid) about 5000 years ago. Surface calcite concentrations ranged from 35-80% and were lowest in bays and along the east shore, but highest in the north central area of the lake. Down-core calcite ranged from 20 to 30% of the sediment, with the balance attributed to silica (quartz, diatoms) and clays. A 0.5-meter-thick nepheloid/fluid mud layer was typically observed at the sediment surface during sampling. The paper also discussed faults and groundwater seepage. The high calcite concentration in surface sediments and cores suggests that carbonate precipitation from the Utah Lake water column, and possibly associated turbidity, have been components of the Utah Lake system for millennia, but not all available sediment core data are consistent with the results or conclusions in this study.

Holden et al. (1994) and Gaeta and Landom (2016) provide useful treatments of water management and fish impacts, with Holden et al. (1994) providing a broader but older view, and Gaeta and Landom (2016) giving a more recent account but with a more narrow focus on June sucker. Holden et al. (1994) states that primary sportfish are channel catfish, walleye, and white bass, and reviews water management in major tributaries (Provo River and Spanish Fork, 46% of total inflow) and approaches to enhance flow and habitat for fish. The publication states that higher flows in rivers and lower, more stable lake levels for habitat (more vegetation, larval transport into lake) are best for fish, especially endemic June suckers. Mitigation of fish passage barriers and diversion impacts are important considerations for river-spawning suckers. The Gaeta and Landom (2016) June sucker monitoring report covers the impacts of drought and carp removal on fish in the lake. Drought lowers lake levels and degrades water quality (higher P; more HABs; smaller zooplankton, which are less desirable for suckers). Carp removal has been quite successful and is showing substantial benefits for other species, including June suckers. A general finding of both fish-related publications is that water flows are heavily modified resulting in degraded habitat and populations, but that higher lake levels are not necessarily favorable for fish or aquatic vegetation. Other than the association of low lake levels with lower water quality and degraded habitat value for fish, the papers do not strongly or quantitatively connect water quality to fish health or recruitment success.

USGS groundwater modeling studies in the Utah Lake area focus on management of aquifer withdrawals for agriculture and municipal supplies rather than on Utah Lake itself, although their findings do have implications for the water budget of the basin, including groundwater inflow and spring inflow. Brooks and Stolp (1995) performed a regional aquifer study and flow model for part of the basin, which was later expanded and updated by Cederberg et al. (2009), and Brooks (2013). Extreme groundwater withdrawal scenarios resulted in water table declines of 22 to 400 feet, and decline or elimination of artesian flow from wells and springs near Utah Lake.

The CUWCD (2007) publication is a very good hydrologic study with excellent figures of past, present, and likely future conditions under different model scenarios. Figures 7, 8, and 9 below, which are reproduced from the CUWCD (2007) study, depict important aspects of Utah Lake's setting with respect to hydrological diversions, lake level changes over time, and changes in annual lake-level variability over time, respectively. The increasing variability of water levels with increased regulation and diversion is identified as a contributing factor to loss of aquatic vegetation, that is, most submerged and emergent vegetation are not adapted to the more extreme fluctuations.

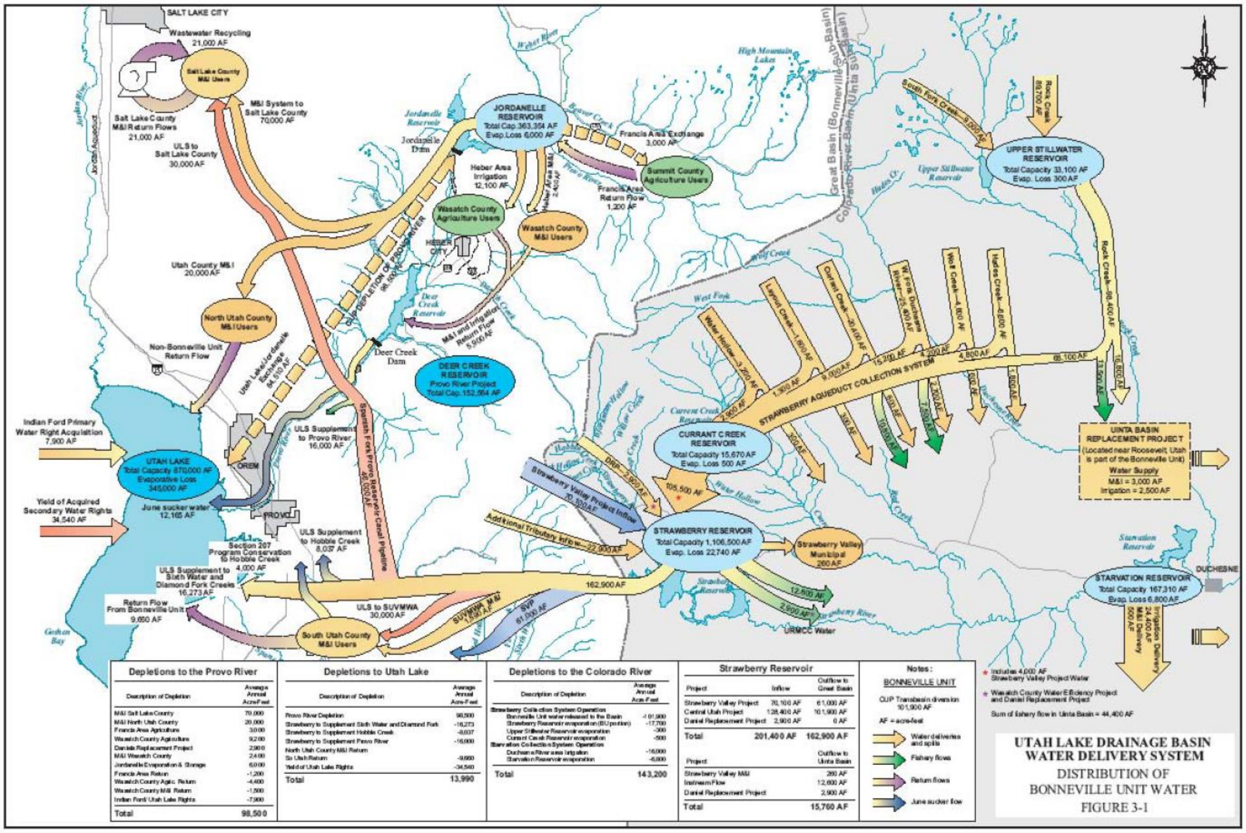

Figure 7. Utah Lake Drainage Basin Water Delivery System (from CUWCD, 2007; Figure 3).

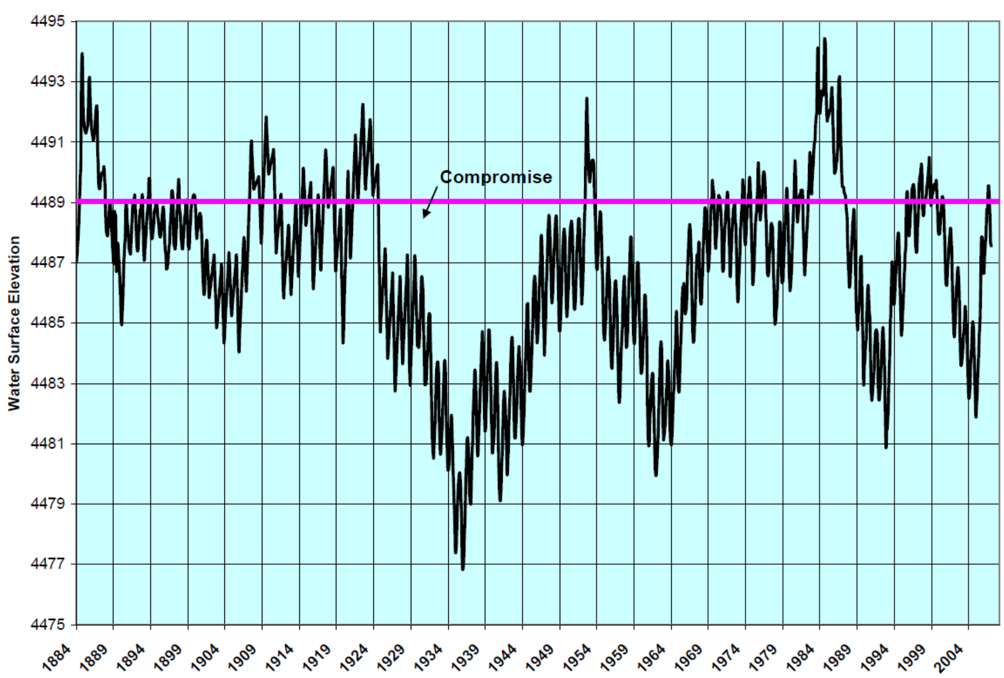

Figure 8. Historical Utah Lake level from 1884 to 2006 (from CUWCD, 2007; Figure 10).

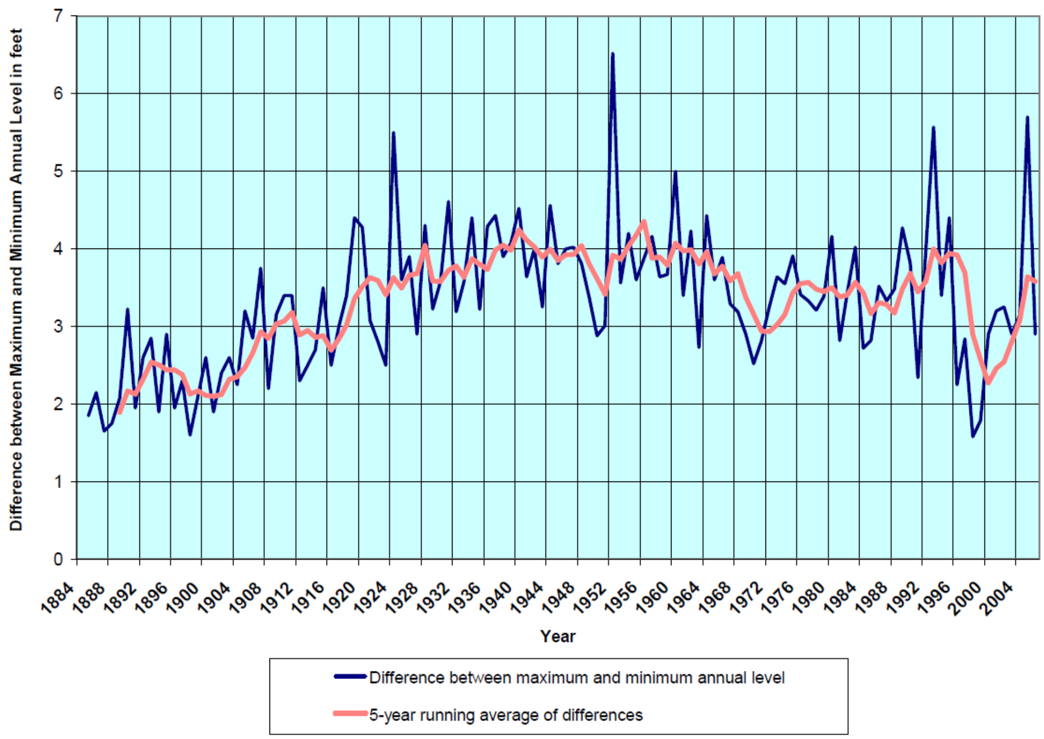

Figure 9. Annual and five-year average within-year variation in Utah Lake level from 1884 to 2006 showing generally increasing variation (doubling) over the historical period from 1884 to the 1930s to 1940 (from CUWCD, 2007; Figure 11).

Gaps

Water quality impacts on fish populations and life stages are not well documented in the studies reviewed, but they are invoked as secondary contributing factors to fish declines and habitat loss, with lake levels and variability typically seen as more important. None of the papers reviewed directly examined linkages between algal blooms and water management, likely because widespread blooms have only recently been recognized as a problem in the lake. Process understanding of the important components of the system (Figure 3), might best be described as uneven.

High-resolution monitoring of lake and tributary water quality, along with numerical models that ingested such data and linked watershed, lake, and biological processes would be necessary to integrate and forecast system conditions to support better management decisions. Some components of this are currently being developed, including continuous in-lake monitoring systems, satellite monitoring, and numerical modeling of nutrient cycling in the lake.

Ability to support the charge questions

Past (a)

Particular historical time periods such as the 1970s are reasonably well documented for Utah Lake in these publications.

Present (b)

Recent conditions, especially through approximately 2006 for hydrological conditions and through 2016 for upper food web conditions (fish), have been compiled and presented in a way to support the charge question about the current state of the system, although these aspects could be better integrated.

Future (c)

Some future simulations have also been undertaken, as reported in CUWCD (2007). Related research projects are currently underway, with reports expected soon, but not yet available for review.

Feasible Improved Stable State of the Lake

The future states of Utah Lake will be the result of both natural and human drivers. Natural drivers include variability in precipitation, wind, and temperature that affect inflow and quality characteristics of tributaries and groundwater, evaporation rates, ice thickness and duration, mixing intensity, sedimentation rates, and atmospheric deposition. Human drivers, which can be controlled to a variable extent, include wastewater discharge, nonpoint urban and agricultural runoff, diversion of water into or out of the basin, outflow regulation and water withdrawal for agriculture or other purposes, stocking and harvest or removal of fish, introduction of non-native species, urban and shoreline development, and habitat degradation or restoration. Management of a naturally dynamic physical and biological system such as Utah Lake, which is dominated by non-native species and competing water demands, is challenging and requires adaptive approaches. The recent appearance or resurgence of toxin-producing cyanobacteria blooms in the lake has added urgency to some management actions that were already underway.

Some of the primary large-scale management responses that have been proposed or undertaken over the last few decades have included:

- stabilizing or raising (deepening) lake levels by modifying inflow volumes, timing, or quality, along with breaking the lake into sub-basins by construction of dikes or dredging bays or larger parts of the lake;
- increased removal of nutrients from wastewater, and reducing urban and agricultural runoff;
- adjusting fish biomass and relative species composition by stocking and harvesting of select species; and
- restoring lake margin habitat, especially at river mouths that historically included large deltas.

Findings

The literature available for this summary provides no clear indication of what the resulting improved state would be, nor of the extent to which the management measures considered to date would attain the desired state. Targeted research, monitoring, and modeling that will help inform management decisions are essential components of sustaining and enhancing the beneficial uses of Utah Lake.

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Appendix A: Annotated Short-List Bibliography of 37 Priority References

	Overall Conclusions and Recommendations	Specific Relevance to the Utah Lake Study	Scientific Credibility
Ashcroft and Merritt 1980	General estimate of flow into southern Utah Lake (37,000 acre feet) and some groundwater quality and patchiness determined from under-ice sampling.	Information is dated.	Masters thesis.
Barnes et al. 1981. Phase 1, Report 2	Winter zooplankton study focused on Goshen Bay and conducted in 1979. Spatially focused study on one bay within the lake and results found rotifers have spatial trends in the shallow areas while other taxa prefer the deeper zones to the north. No additional recommendations for other portions of the lake.	Relevant but spatially limited. Little in the way of lake-wide applicability and a bit focused on an older data set that appears better covered by the updated Richards and Miller (2017) study	Prepared for USBoR. No external review cited. Work appears to be credible.
Barnes et al. 1981. Phase 1, Report 3 & 8	Littoral zone benthic macroinvertebrate community analysis conducted in 1978 and 1979. Provided a good description of macroinvertebrate community by substrate type. Concluded that most of the macroinvertebrate stock is located in Goshen Bay, and appeared to be linked to the large rubble areas. No additional recommendations for other portions of the lake.	Relevant, particularly for substrate characterization from the 1970s era, but older data set for macroinvertebrate community that appears better covered by the updated Richards and Miller (2017) study	Prepared for USBoR. No external review cited. Work appears to be credible.
Barnes et al. 1981. Phase 1, Report 6	Littoral zone benthic macroinvertebrate community analysis conducted in 1978 and 1979, but more broadly encompassing. Conclusions are that sand/ooze community is relatively homogeneous lake-wide, rocky substrates have high densities of macroinvertebrates, emergent plant communities are as important as substrate size for increased composition, and Goshen Bay offers diverse habitat types and a high density and diversity of organisms.	Relevant, particularly for substrate characterization from the 1970s era but older data set for macroinvertebrate community that might be better covered by the updated Richards and Miller (2017) study, although link mentioned by the Barnes et al study to vegetative community remains valuable.	Prepared for USBoR. No external review cited. Work appears to be credible.
Barnes et al. 1981. Phase 1, Report 7	Zooplankton study conducted in 1978 and 1979, but more broadly encompassing. Zooplankton dynamics exist across all habitat types across the lake and among substrate types. Rotifers made up a significant part of the community, except in sandy sites. Dominant types changed across the year, and wind was an important driver of composition.	Relevant, particularly for substrate characterization from the 1970s era, but older data set for zooplankton community that might be better covered by the updated Richards and Miller (2017) study.	Prepared for USBoR. No external review cited. Work appears to be credible.

	Overall Conclusions and Recommendations	Specific Relevance to the Utah Lake Study	Scientific Credibility
Barnes et al. 1982	Compares soft-ooze community structure based upon transects sampled in Goshen Bay, Provo Bay, and North Mid and South portions of the main Lake. Data were analyzed to see if any sampled areas were significantly different from others. Comparisons were made of Oligochaetes and three species of Chironomid. For all three dates there were no significant differences of Oligochaetes between Goshen Bay and Main Lake. Provo Bay was found to be different than Main Lake for Oligochaetes for two of three sampling periods. There were no significant differences of C. frommeri between Goshen Bay and Main Lake. The overall conclusion was that lower densities of Oligochaetes and Chironomids are found in Provo Bay than in Goshen Bay and the Main Lake.	Little, beyond documenting number and types of macroinvertebrates in three zones of the lake.	Prepared for USBoR. No external review cited. Work appears to be credible.
Barnes, J.R. and Toole, T.W. 1981	A literature review of macroinvertebrates and zooplankton communities of Utah Lake. Provides a synthesis of study trends from previous studies. Interesting finding includes that no clear correlation between phytoplankton and zooplankton populations were evident.	Relevant literature summary and characterization from a 1970s era assessment, and may be valuable as a summary resource. This might be updated by the updated Richards and Miller (2017) study.	Peer-reviewed and credible.
Bradshaw et al. 1973	Lake receives influent wastewater from nine municipalities. Salinity of the lake increased around 1900 with a 5-foot drop in lake level. Algal blooms linked to wastewater-driven eutrophication covered all of Provo Bay and part of Utah Lake in 1969 and 1970, with associated odor and nuisance insect issues. Some material repeated in 1981 publications.	Information is dated but an important record of older algal blooms. Productivity is stated to be nitrogen limited, but basis is unclear.	Peer-reviewed applied science and engineering journal.
Brimhall and Merritt 1981	Reviews prior studies of a 520-cm sediment core and 140 surface core samples; no direct age control on sediment core. Sedimentation rate estimated at 0.8 to 1.5 mm/yr. Surface precipitated calcite concentrations ranged from 35-80%; lowest in bays and along east shore, highest in center north; downcore calcite ranged from 20-30%.	Sediment core data and understanding of modern sediment property data are important for understanding past and present conditions in Utah Lake.	Short monograph from regional peer-reviewed publication. Not all conclusions are well-supported.
Brotherson 1981	Description of aquatic and semiaquatic plant communities, distribution and densities around the main lake and its major bays, as they appeared in the early and mid-1970s.	Relevant in the early settlement description as well as 1970s lake community description. Unsure about how current conditions of plant community compares to the Brotherson description.	Peer-reviewed and credible.
Bushman 1980	This study is designed to determine the distinctive physical features of the lake, primarily in regard to those that affect the rate of sedimentation. It provides several historical citations of the condition of the lake in the early 20th century, describing how the lake had changed from being clear water with abundant macrophytes to turbid water lacking macrophytes. It calculates an average rate of deposition from 1849 to 1972 of 1.38 cm per year, based on dandelion pollen in sediment cores, and concludes that rate of deposition has increased since European colonization.	Provides estimate of deposition rate, which is an important component to water/sediment quality models. Also provides a good summary of others' description of historical water quality.	Published in Brigham Young University Geology Studies, in which articles are externally reviewed by at least two qualified persons.

	Overall Conclusions and Recommendations	Specific Relevance to the Utah Lake Study	Scientific Credibility
BYU 1982	Only available as summarized (albeit in detail) in Phase II summary report. Provides description of water balance, water quality, sediment/habitat characteristics, algal communities, and benthos.	Comprehensive discussion of data relevant to in-lake water quality conditions and watershed loading of nutrients to Utah Lake, but only up to 1980.	Study report prepared for Bureau of Reclamation. Extent of external review unknown. Appears highly credible.
Callister 2008	Develops and calibrates 3-dimensional hydrodynamic model of Utah. The model was deemed useful in generally characterizing the direction and velocity of water currents in Utah Lake, and providing a way to predict general temperature distributions over time. Conclusions were that it was determined that those factors that most strongly influence the water temperatures are the air temperature, incident short wave radiation, wind speed, and wind direction, with relative humidity and cloud cover having a lesser degree of influence. The factors that have the greatest effect on the flow field are the wind direction and wind speed.	May provide some general understanding of typical current patterns in Utah Lake. Model uses inputs from a range of years and only provides results for a hypothetical year. Less than rigorous calibration.	Master's Thesis.
Clark and Appel 1983	Comprehensive and well-illustrated regional aquifer study, supersedes earlier studies in scope and quality, although less of a focus on Utah Lake specifically.	Relevant as background for consideration of groundwater influence on watershed and lake.	High credibility, given rigorous internal USGS review and publication standards.
CUWCD 2007	Very good hydrological study with excellent figures of past conditions from 1884 to 2006. Study conducted as part of June sucker recovery program, with special emphasis on rooted aquatic vegetation restoration as juvenile habitat. Salinity model (LKSIM2000) was used to simulate natural, current, and future conditions.	Important for understanding history and complexity of water level management in Utah Lake.	High-quality consultant report (HDR, Inc.) reviewed by water agency.
Davis 2006	Pilot test developing a model to correlate chlorophyll *a* to satellite imagery. A correlation was developed, but conclusion is that more data are needed to develop a model with sufficient accuracy.	Little. Provides 2-d mapping of chlorophyll concentrations observed in 5/91, 7/97, 8/89, and 8/90, but subject to an r^2 of 0.56 for the predictive regression.	Master's Thesis. Sufficiently credible to serve as proof of concept, and results are appropriately qualified.
Davis 2009	A pilot study assessed statistical correlations of Landsat satellite imagery from three years in the 1990s with 27 ground-truth chlorophyll *a* samples from Utah Lake.	Development of remote sensing methods will be important for future monitoring of lake conditions and reconstruction of past surface conditions from archived images.	Masters thesis.
Fuhriman and Merritt 1981	Mostly a data report of approximately 76 tributary flow measurement sites to calculate lake inflows, some with more than one station per tributary. Much of the information here is repeated in Fuhriman et al., 1981.	Relevant as a snapshot of 1970s surface water inflow conditions.	Agency report, no documentation of peer review. Authors are BYU faculty.
Fuhriman et al. 1981	Inflow and chemistry measurements on 52 tributaries and estimates from unmeasured tributaries, as well as estimates of groundwater inputs, and evaporation are reported based on early 1970s studies. Productivity is stated to be nitrogen limited, but basis is unclear.	Relevant as snapshot of historical inflow and water quality conditions in early 1970s.	Short monograph from regional peer-reviewed publication. Conclusions about natural versus human nutrient loading to the lake and associated mitigation potential are not fully supported by data.

	Overall Conclusions and Recommendations	Specific Relevance to the Utah Lake Study	Scientific Credibility
Gaeta and Landom 2016	Utah State monitoring report of impacts of drought and carp removal on fish in the lake. Drought lowers lake level and degrades water quality (higher P, more HABs, smaller zooplankton; less desirable for June suckers).	Relevant as a recent status report of linkage between fish populations, water levels, and management actions (e.g., carp removal).	Status report to agency, but relatively high quality and credibility.
Gaeta et al. 2016	Primary objectives of the overall work to determine if ecosystem change has occurred in Utah Lake, explicitly as a function of carp removal, and to differentiate effects of ecosystem disturbances, such as drought, from the effects of carp removal. Current report does not provide any data, and just describes methodological specifics and spatial and temporal attributes of Utah Lake data collected by USU and DWQ Parameters covered include water quality, phytoplankton, zooplankton, macroinvertebrates, fish (and fish diet), stable isotopes, and macrophytes.	Will be highly relevant to describing in-lake water quality conditions when project is completed.	Extent of external review unknown. Provides no actual data, so scientific credibility may not be especially relevant.
Heckmann et al. 1981	Offers a description of the Utah Lake fisheries resources and its developments pre-settlement to mid- 1970s period.	Relevant and valuable timeline. The report provides a valuable timeline of transitions in lake management, development, discharges, inflow controls and fisheries management and harvest. The report provides a valuable resource of changes at the species and community level as water quantity and quality has changed over time.	Peer-reviewed and credible.
Hogsett and Goel 2013	Designed to; (1) quantify phosphorus speciation/fractionation in sediments, (2) evaluate the mineralogy of sediments using X-ray diffraction, (3) evaluate sediment and water column oxygen demand; and (4) evaluate sediment nutrient fluxes at five additional locations under varying pH and DO. Median of twelve sites of 61% of sediment P found bound to Ca. Reported SOD ranges from 0.9 to 4.6 $g/m^2/d$. Half of reported P flux values were zero, remainder ranged from 0.01 to 0.39 $g/m^2/d$.	Somewhat relevant in terms of describing internal cycling and biological availability of nutrients. P flux experiments appear to be conducted with a duration of <12 hours. Note that calculated Calcium-bound P is higher than reported by Randall.	Master's Thesis. Insufficient detail provided to fully assess credibility (e.g., no presentation of concentration over time for SOD). P-flux measurements appear to have a duration of less than 12 hours.
Holden et al. 1994	Reviews water management in major tributaries (Provo River and Spanish Fork, 46% of total inflow) and approaches to enhance flow and habitat for fish: higher flows in rivers, lower and more stable lake levels for habitat (more vegetation, larval transport into lake); mitigation of fish passage barriers and diversion impacts for migration.	General relevance, although more recent reports by Landom and coauthors may be more useful.	Consultant report (BIO-WEST, Inc.), generally high quality.

	Overall Conclusions and Recommendations	Specific Relevance to the Utah Lake Study	Scientific Credibility
Horns 2005	Summarizes the current conditions of Utah Lake in terms of: composition of sediments being deposited in the lake, the rate of deposition of the sediments, the hydrology of the lake, factors in the drainage basin that may affect the water quality, the flora and fauna of the lake, special biological designations within and adjacent to the lake, threatened and endangered species that depend on the lake, human use of the lake, and the local planning and zoning that may affect the lake. Based on literature review and interviews. Report includes no original research. Concludes that that human disturbance has played a dominant role in geochemical transforming of Utah Lake, mainly through cultural eutrophication that triggers an influx of nutrients and causes algal blooms.	Very relevant to the study question, "What was the pre-settlement condition of Utah Lake with respect to nutrients and ecology?" Doesn't define pre-development condition, but demonstrates that human disturbance has played a dominant role in geochemical transforming of Utah Lake, mainly through cultural eutrophication that triggers an influx of nutrients and causes algal blooms.	Extent of external review unknown. Only cites the work of others, so scientific credibility may not be especially relevant.
Janetski 1990	Provides overview of the lake's ecological and cultural history viewed through the findings of archaeological and ethnohistorical research. It describes the pre-settlement conditions and the impacts that settlement had on the lake. Of the twelve fish species native to the Utah Lake system, eleven are now extremely rare or extinct. As with the fishery, the native vegetation in the valley and around the shores of the lake has been drastically altered in distribution and composition due to development, the introduction of exotic plant species, and introductions of exotic fishes, especially the carp.	Provides a good summary of others' description the pre-settlement conditions and the impacts settlement had on the lake. Focus on fish impacts and native macrophyte impacts	Published in Utah Historical Quarterly, articles in which undergo review by editorial staff.
King and Merritt 1981	This is mostly a groundwater inflow and quality (TDS and major ions) data report, which was used to develop inputs for the LKSIM model. Shallower Pleistocene aquifers are noted as having lower water quality (higher TDS) than deeper Tertiary aquifer; some flowing artesian wells noted.	Relevant as snapshot of historical groundwater inflow and water quality conditions.	Agency report, no documentation of peer review.
Landom 2010	Study assessing components of a lake-wide food web model for Utah Lake with the intent to understand how the introduced species and size classes have and could affect native fish reproduction and survival within the lake. Three food web models are presented and compared: stable isotope-derived food web, a quantified diet-derived food web, and finally, an integrated stable isotope and quantified diet food web with inferences from the comparison. Substantial predation was occurring on the early life stages of Utah Lake fishes, including native fishes, and it was not being observed using stomach content analysis. Of the many species and size-classes of introduced sport fish, white bass appears to be an important threat.	Relevant and recent report and developed specifically for Utah Lake to support future ecological model efforts.	Final report submitted to the June Sucker Recovery Implementation Program. Appears to be an MS thesis; external review is uncertain but appears credible.

	Overall Conclusions and Recommendations	Specific Relevance to the Utah Lake Study	Scientific Credibility
Landom et al. 2010	Second phase of analysis based on Landom (2010) to use a food web model approach to understand: 1) food web responses to removal of carp and white bass; 2) fish predator impacts on June sucker and juvenile carp; and 3) the re-establishment of a prey species (Utah chub). Applied a combination of top-down and bottom-up food web models to develop hypotheses, identified information gaps, and provided many management suggestions that support biomanipulation and fish conservation in Utah Lake. The bioenergetics modeling results suggest that under the current conditions predation by introduced piscivores (white bass) may be too substantial to support self-sustaining Utah Lake sucker populations, although recent management appears to be making improvements for June suckers.	Relevant and recent report. The modeling is developed for and based on lake-specific ecological data and appears valuable for an ecosystem and water quality model.	Final report submitted to the June Sucker Recovery Implementation Program. External review uncertain but appears credible based on collaboration list.
Landom et al. 2014	Reports on the planning and design of a long-term monitoring program for several Utah Lake ecosystem components, using an ecosystem conceptual model as a guide. Providing recommendations for sampling strategies for each ecosystem component. Results highlight need to consider sampling effort during monitoring program development, and includes a framework to facilitate adaptive management.	Relevant and recent report. The data and approach appear to provide valuable with broadly applicable components (1), water quality, (2) phytoplankton, (3) zooplankton, (4) macroinvertebrates, (5) fisheries, (6) and macrophytes) necessary for building and maintaining a broadly useful ecosystem model.	Final report submitted to the June Sucker Recovery Implementation Program. External review uncertain but appears credible based on collaboration list.
Liljenquest 2012	Reported sample results from 2009 through 2011 for tributaries, WWTPs, and Jordan River outlet to develop flow and TDS concentration trend lines at Utah Lake to understand TDS loading, and loss from the Jordan River; used to calibrate LKSIM salinity model.	Relatively recent dataset linking TDS and flow for Utah Lake system, useful for understanding near-current salt budget.	Masters thesis.
Liljenquist 2012	Correlates TDS and ion concentrations in tributaries with flow rates and time of year. Analyses based upon monthly to twice-monthly water samples collected at 18 different sites from Utah Lake tributaries and the Jordan River from March 2009 to May 2011, The regressions developed here generated more accurate predictions of TDS and ion concentrations than the existing Utah Lake Simulation Model LKSIM equations. No nutrient data were collected during this study	Little.	Master's Thesis. Use of polynomial regressions may result in very inaccurate predictions if extrapolated to flow conditions beyond those used for model development.
Macharia 2012	Contains three separate studies, only one of which is directly related to Utah Lake. Reconstructs historic and prehistoric environments through geochemical proxies of 15N enrichment, pollen, charcoal, and loss on ignition at 550 °C and 950 °C in sediment cores. It concludes, based upon shifts in organic matter fluxes and productivity resulting from cultural eutrophication manifested in C:N ratios, that disturbance at the time of establishment of agriculture and urban settlement around Utah Lake has altered nutrient and particulate matter fluxes into the lake.	Very relevant to the study question, "What was the pre-settlement condition of Utah Lake with respect to nutrients and ecology?" Does not define pre-development condition, but indicates that pre-development and post-development conditions are different.	Doctoral Dissertation.

	Overall Conclusions and Recommendations	Specific Relevance to the Utah Lake Study	Scientific Credibility
Merrell 2015	Measures TP and Fe content of 56 lake and 10 riparian sediments cores, as well as P flux from lake sediments under toxic and anoxic conditions. Total P concentrations in surface sediment (0-4 in.) varied throughout Utah Lake ranging from 306 to 1710 ppm, with a mean value of 711 ppm. The median Fe:P ratio was 15, which was considered a threshold at which it may be possible to control internal P-loading by keeping the surface sediment oxidized. Additional sediment cores were collected to model the P release from the sediments, but no actual flux measurements were provided (only summary plots of phosphorus concentration over time).	Somewhat relevant in terms of describing internal cycling and biological availability of nutrients. Sediment flux only presented qualitatively (i.e., increase in concentration over time), no actual flux calculations provided.	Master's Thesis.
Narteh 2011	Satellite imaging was shown to be valuable for detecting lake-wide bloom conditions; usually strong association with bays and nearshore (nutrient loading sources, longer residence time, more light penetration). Builds on prior work of Davis, 2009.	Development of remote sensing methods will be important for future monitoring of lake conditions and reconstruction of past surface conditions from archived images.	Masters thesis.
Randall 2017	Purpose of the study was to quantify lake sediment phosphorus characteristics. A total of 26 sediment samples were collected with P concentrations ranging from 306 to 1894 ppm, and highest in Provo Bay. Results show ~25-50% of P is bound with calcium minerals. Study also included batch sorption experiments, which indicate that lake sediments have a capacity to absorb 70-96% of water column phosphorus over the range of 1 to 10 mg/L P.	Somewhat relevant in terms of describing internal cycling and biological availability of nutrients. Note that calculated Calcium-bound P is lower than reported by Hogsett and Goel.	Master's Thesis.
Richards, D. C. and T. Miller 2017	Provided a recent and detailed assessment of Utah Lake phytoplankton, zooplankton and benthic macroinvertebrate communities to understand the lake food web dynamics. The phytoplankton assemblage clearly differed both spatially and temporally, as did most individual taxa densities. Zooplankton are the primary top-down, higher trophic-level controller of phytoplankton and HABs. Assemblages significantly differed by locations and month. Provo Bay zooplankton assemblages were spatially and temporally from other areas of Utah Lake and will be analyzed separately in ongoing analyses. Zooplankton assemblages were also affected by depth, with several important taxa occurring at greater depths than others. The study assesses the contribution of benthic macroinvertebrates as they affect nutrients in the lake. Provo Bay benthic assemblages are unique compared to the remainder of the lake.	Relevant and updated, and covers key components of the food web. Offers numeric and conceptual models for components of the food web dynamics.	Study prepared for the Wasatch Front Water Quality Council. Extent of external review unknown. Appears highly credible.

Appendix B: Cited Papers Considered in the Literature Summary

This table includes the 100 "prioritized for review" papers considered in this study. The table includes a priority number of 1-4 (column 1) assigned to each paper, as well as the assigned topic category (column 5), charge question and secondary category of support, where applicable. With the exception of some supplemental papers that were added after the initial review of the draft report (see p. 3-4), only papers (n=37 in the original prioritized list) from categories 1 and 2 were included in the comprehensive review. Entries in the table below are sorted by paper category (column 4), and then alphabetically by author for the first part of the table (through p. 49), and then alphabetically by author after that.

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
1	Abu-Hmeidan, H.Y.	2018	Characterizing Total Phosphorus in Current and Geologic Utah Lake Sediments: Implications for Water Quality Management Issues	3	a	N.A
1	Ashcroft, W., and L. B. Merritt.	1980	Utah Lake phase I report #1: quantity and quality of Goshen Bay inflows. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	5	b	N/A
1	Barnes, J. R., D. K. Shiozawa, J. V. McArthur, and R. Y. Oberndorfer.	1981	Utah Lake phase 1 report #3 and #8 combined: Utah Lake littoral community analysis: October 1978–May 1979. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	N/A
1	Barnes, J. R., D. K. Shiozawa, J. V. McArthur, and R. Y. Oberndorfer.	1981	Utah Lake phase 1 report #7: Utah Lake littoral community analysis: Intensive site zooplankton studies Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	N/A
1	Barnes, J. R., D. K. Shiozawa, R. Y. Oberndorfer, and J. V. McArthur.	1981	Utah Lake phase 1 report #6: Utah Lake littoral benthic community: an intensive study. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	N/A
1	Barnes, J.R. and T.W. Toole	1981	Macroinvertebrates and Zooplankton Communities of Utah Lake: A Review of the Literature. 1981.	4	b	N/A
1	Brotherson, J.D.	1981	Aquatic and Semiaquatic Vegetation of Utah Lake and its Bays. 1981.	4	b	N/A
1	Callister, E. V.	2008	A three-dimensional, time-dependent circulation model of Utah Lake. M. S. thesis. Utah State University, Logan, Utah.	1	b	N/A

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
1	CUWCD, and S. M. Thurin.	2007	Utah Lake water level fluctuation. Final report to the June Sucker Recovery Implementation Program. Central Utah Water Conservancy District, Orem, Utah.	5	b	N/A
1	Fuhriman, D.K., L.B. Merritt, A.W. Miller, and H.S. Stock	1981	Hydrology and Water Quality of Utah Lake. 1981.	5	b	1
1	Gaeta, J., R. Dillingham, and K. Landom.	2016	Utah Lake ecosystem metadata. Ecology Center and Watershed Sciences Department, Utah State University, Logan, UT.	2	b	4
1	Hansen, C.	2017	Spatiotemporal Variability of Lake Water Quality in Context of Remote Sensing Models	1	b	N/A
1	Hogsett, M., and R. Goel.	2013	Determination of nutrient fluxes and sediment oxygen demand at selected locations in Utah Lake. Civil & Environmental Engineering, University of Utah, Prepared for: Utah Division of Environmental Quality.	3	b	N/A
1	Horns, D.	2005	Utah Lake comprehensive management plan resource document. Utah Valley State College, Orem, Utah.	1	b	2, 4
1	Janetski, J. C.	1990	Utah Lake: its role in the prehistory of Utah Valley. Utah Historical Quarterly 58:5-31.	1	a	N/A
1	Liljenquest, Gordon Killarney	2012	Study of Water Quality of Utah Lake Tributaries and Jordan River Outlet for the Calibration of the Utah Lake Water Salinity Model (LKSIM)	2	b	1
1	Macharia, Anthony Njuguana	2012	Reconstruction of Paleoenvironments Using a Mass-Energy Flux Framework (Utah Lake)	1	a	N/A
1	Merrell, P. D., W. A. Miller, B. M. Borup, and G. P. Williams	2015	Utah Lake Sediment Phosphorus Analysis	3	b	2
1	Merritt, L.B., A. W. Miller	2017	Nutrient Loadings to Utah Lake	2	b	
1	Narteh, Victor Nii Afum	2011	Mapping and Modeling of Chlorophyll-a Concentrations in Utah Lake Using Landsat 7 ETM+ Imagery	1	b	N/A
1	Olsen, J.M.	2018	Measuring and Calculating Current Atmospheric Phosphorous and Nitrogen Loadings on Utah Lake Using Field Samples, Laboratory Methods, and Statistical Analysis: Implication for Water Quality Issues	2	b	N/A
1	Randall, M. C.	2017	Characterizing the Fate and Mobility of Phosphorus in Utah Lake Sediments	3	b	N/A
1	Rathee, G	2017	Detection of Algal Blooms in Lakes Using Sentinal-1 C-band SAR Images	1	b	N/A

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
1	Richards, D.C. and T.M. Miller,	2016	UTAH LAKE RESEARCH 2016 Progress Report A preliminary analysis of Utah Lake's unique foodweb with a focus on the role of nutrients, phytoplankton, zooplankton, and benthic invertebrates on HABs	4	b	1, 3
1	US FWS	2010	Final EA for removal and control of nonnative carp in Utah Lake to support June Sucker recovery	5	c	
1	UTDEQ	2016	UTAH LAKE NUTRIENT MODEL SELECTION REPORT	2	b	N/A
2	Barnes, J. R., D. K. Shiozawa, J. V. McArthur, and R. Y. Oberndorfer.	1982	Utah Lake phase 1 report #5: the soft-ooze benthic communities of Utah Lake Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	2	b	N/A
2	Barnes, J. R., D. K. Shiozawa, J. V. McArthur, and R. Y. Oberndorfer.	1981	Utah Lake phase 1 report #2: winter zooplankton communities of Goshen Bay Utah Lake, Utah, USA. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	N/A
2	Bolland, R. F.	1974	Paleoecological interpretation of diatom succession in recent sediments of Utah Lake. Unpublished dissertation, University of Utah.	1	a	N/A
2	Bradshaw, J. S., R. B. Sundrud, D. A. White, J. R. Barton, D. K. Fuhriman, E. L. Loveridge, and D. R. Pratt.	1973	Chemical Response of Utah Lake to Nutrient Inflow. Journal Water Pollution Control Federation, 45. 1973.	1	b	N/A
2	Brimhall, W.H. & L.B. Merritt	1981	Geology of Utah Lake: Implications for Resource Management. 1981.	5	b	1
2	Brooks and Stolp	1995	Hydrology and simulation of ground-water flow in Southern Utah and Goshen Valleys, Utah	5	b	N/A
2	Brooks, L.E.	2013	Evaluation of the Groundwater Flow Model for Southern Utah and Goshen Valleys, Utah, Updated to Conditions through 2011,with New Projections and Groundwater Management Simulations	5	b	N/A
2	Bushman, J.R.	1980	The Rate of Sedimentation in Utah Lake and the Use of Pollen as an Indicator of Time in Sediments	1	a	N/A
2	Cederberg et al.	2009	Hydrology of Northern Utah Valley, Utah County, Utah, 1975-2005	5	b	N/A
2	Clark, C. W. and C. L. Appel.	1985	Ground-Water Resources of Northern Utah Valley, Utah	5	b	N/A
2	Davis, Tina	2006	Quantifying Chlorophyll a Content Through Remote Sensing: A Pilot Study of Utah Lake	1	b	N/A

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
2	Fuhriman, D. K., and L. B. Merritt.	1981	Utah Lake Phase 1 Report #12, Utah Lake surface inflows and outflows: 1930-1980. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	5	b	N/A
2	Gaeta, J., and K. Landom.	2016	A whole-ecosystem response of a shallow lake to drought and an invasive carp removal, with an emphasis on endangered fish conservation. Utah State University, Ecology Center and Department of Watershed Sciences.	5	c	4
2	Heckmann, R.A. and L.B. Merritt. Preface.	1981	Great Basin Naturalist Memoirs, Utah Lake Monograph. Brigham Young University. Number 5:1-2. 1981.	4	a	N/A
2	Holden, P. B., C. N. Goodwin, and K. D. Theis.	1994	A study to determine appropriate water management actions to enhance native and sportfish populations in Utah Lake: summary of existing information and preliminary feasibility study. BIO/WEST, Inc., Logan, Utah.	5	b	4
2	Javakul, A., J.A. Grimes, and S.R. Rushforth	1980	Diatoms in Sediment Cores in Utah Lake, Utah. U.S. Bureau of Reclamation WHAB Phase One Report #16	1	a	N/A
2	King, R. V., and L. B. Merritt.	1981	Utah Lake Phase 1 Report #17: ground water quality along the eastern margin of Utah Lake. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	2	b	1
2	Landom, K.	2010	Utah Lake food web part I – Introduced sport fish and fish conservation in a novel food web: evidence of predatory impact. Final report submitted to the June Sucker Recovery Implementation Program. Ecology Center, Utah State University, Logan, Utah.	4	b	N/A
2	Landom, K., T. A. Crowl, P. Budy, G. P. Thiede, and C. Luecke.	2010	Utah Lake food web part II – Biomanipulation and fish conservation in the shallow, eutrophic, Utah Lake: a combined bottom-up and top-down food web modeling approach. Final report submitted to the June Sucker Recovery Implementation Program. Ecology Center, Utah State University, Logan, Utah.	4	b	
2	Rushforth, S. R., J. Grimes, and L. E. Squires.	1981	Utah Lake Phase 1 Report #31: a study of the algal communities from the littoral zone of Utah Lake, Utah. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	N/A

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
2	Rushforth, S. R., J. Grimes, L. E. Squires, and A. Javakul.	1981	Utah Lake Phase 1 Report #32: a study of planktonic floras collected from historic sites on Utah Lake, Utah, USA. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	N/A
2	Strong, A.E.	1974	Remote Sensing of Algal Blooms by Aircraft and Satellite in Lake Erie and Utah Lake	1	b	N/A
2	Whiting, M. C., J. D. Brotherson, and S. R. Rushforth	1978	Environmental interaction in summer algal communities of Utah Lake	4	b	N/A
3	Barnes, J. R., D. K. Shiozawa, R. Y. Oberndorfer, and J. V. McArthur.	1981	Utah Lake phase 1 report #4: Utah Lake transect zooplankton analysis. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.			
3	Barnes, J.R., D.K. Shiozawa, J.V. McArthur, and R.Y. Oberndorfer	1978	Utah Lake Littoral Community Analyses: October 1978 and May 1979. U.S. Bureau of Reclamation WHAB Phase One Report #3 and #8 . 1981	3	b	
3	Barnes, J.R., D.K. Shiozawa, J.V. McArthur, and R.Y. Oberndorfer	1981	The Soft Ooze Benthic Communities of Utah Lake. U.S. Bureau of Reclamation WHAB Phase One Report #5. 1981	3	b	
3	Barnes, J.R., D.K. Shiozawa, J.V. McArthur, and R.Y. Oberndorfer	1981	Utah Lake Littoral Benthic Community: an Intensive Study. U.S. Bureau of Reclamation WHAB Phase One Report #6. 1981	4	b	
3	Barnes, J.R., D.K. Shiozawa, J.V. McArthur, and R.Y. Oberndorfer	1981	Utah Lake Littoral Community Analyses: Intensive Site Zooplankton Studies. U.S. Bureau of Reclamation . 1981 Phase 1 #7	4	b	
3	Barnes, J.R., D.K. Shiozawa, J.V. McArthur, and R.Y. Oberndorfer	1981	Utah Lake Transect Zooplankton Analysis. U.S. Bureau of Reclamation WHAB Phase One Report #7. 1981	4	b	
3	Barnes, J.R., D.K. Shiozawa, J.V. McArthur, and R.Y. Oberndorfer	1981	Winter Zooplankton Communities of Goshen Bay, Utah Lake, Utah. U.S. Bureau of Reclamation WHAB Phase One Report #2. 1981			
3	Bingham, Clair C.	1975	Recent Sedimentation Trends in Utah Lake. Brigham Young University Geology Studies, Vol. XXII, pt.1. Brigham Young University Press. Provo, UT. 1975.			
3	BIO-WEST.	2008	Lower Provo River ecosystem flow recommendations: final report to the Utah Reclamation Mitigation and Conservation Commission. BIO-WEST, Inc., Logan, Utah.	N/A	N/A	

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
3	Bolland, R. F.	1974	Paleoecological interpretation of diatom succession in recent sediments of Utah Lake. Unpublished dissertation, University of Utah. 1974.			
3	Brigham Young University.	1980	Quantity and Quality of Goshen Bay Inflows. WHAB Phase I Report #1. 1980. (prepared for U.S. Bureau of Reclamation)	5	b	N/A
3	Brigham Young University.	1982	Water Quality. Hydrology and Aquatic Biology of Utah Lake. WHAB Phase I Summary. 1982. (prepared for U.S. Bureau of Reclamation)	Duplicate	Duplicate	N/A
3	Brigham Young University.	1982	WHAB Phase I Summary: Water Quality, Hydrology and Aquatic Biology of Utah Lake. Eyring Institute, Inc. Brigham Young University. 1982			
3	Brimhall, W. H.	1973	Recent History of Utah Lake As Reflected in Its Sediments: A Primary Report. Brigham Young University Geological Studies, Vol. 19, pt. 2, pp 121-126. 1973.			
3	Brimhall, W. H., and L. B. Merritt	1980	Utah Lake Phase 1 Report #9, Goshen Bay sediments: carbonate concentrations, particle sizes, shrinkage, and conversion of sediment to soil. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.			
3	Cameron, F. K.	1905	The Water of Utah Lake. American Chemical Society Journal 27:113-116. 1905.			
3	Central Utah Water Conservancy District.	1989	1989 Investigation of Mineral Springs at Bird Island and Lincoln Point-Utah Lake. Orem, Utah. 1990.			
3	Clark, C. W.	1984	The Ground-Water System and Simulated Effects of Ground-Water Withdrawals in Northern Utah Valley, Utah	N/A	N/A	
3	Coombs, R. E.	1970	Aquatic and semi-aquatic plant communities of Utah Lake. Ph. D. dissertation. Brigham Young University, Provo, Utah.			
3	Cottam, W. P.	1926	An ecological study of the flora of Utah Lake, Utah. Ph. D. dissertation. University of Chicago, Chicago, Illinois.			
3	Crowl, T. A., and S. A. Miller.	2004	Development of macrophytes in Utah Lake: macrophyte additions and carp exclusions. 2003 Annual Report. Ecology Center, Department of Fisheries and Wildlife, Utah State University, Logan, Utah.	4	b	
3	Eyring Institute.	1982	WHAB Phase I Summary. Water Quality, Hydrology and Aquatic Biology of Utah Lake. Brigham Young University. 170 pp. 1982			

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
3	Fuhriman, D. K., L. B. Merritt, A. W. Miller, and H. S. Stock.	1974	Hydrology and water quality of Utah Lake. Brigham Young University, Provo, Utah.			
3	Grimes, J.	1980	Taxonomy and ecology of diatoms of surface sediments of Utah Lake, Utah, U.S.A. Ph. D. dissertation. Brigham Young University, Provo, Utah.	4	b	
3	Grimes, J., and S. R. Rushforth.	1980	Utah Lake Phase I Report #13: ecology of diatoms of surface sediments of Utah Lake, Utah, U.S.A. Brigham Young University, Provo, Utah.	4	b	
3	Grimes, J., S. R. Rushforth, and A. Javakul.	1980	Utah Lake Phase I Report #14 & #15: Taxonomy of diatoms of surface sediments of Utah Lake, Utah. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	
3	Grimes, J.A.	1980	Taxonomy and Ecology of Diatoms of Surface Sediments of Utah Lake, Utah. Brigham Young University. Dept. of Botany and Range Science, Ph.D. Dissertation. 1980	4	b	
3	Grimes, J.A. and S.R. Rushforth	1980	Ecology of Diatom Surface Sediments of Utah Lake, Utah. U.S. Bureau of Reclamation WHAB Phase One Report #13. 1980	4	b	
3	Grimes, J.A. and S.R. Rushforth	1982	Diatoms of Recent Bottom Sediments of Utah Lake, Utah. Bibliotheca Phycologica 55. 1982, 69 plates 179 p.. 1982	4	b	
3	Grimes, J.A., A. Javakul, and S.R. Rushforth	1980	Taxonomy of Diatoms of Surface Sediments of Utah Lake, Utah. U.S. Bureau of Reclamation WHAB Phase One Report # 14 - #15. 1980	4	b	
3	Harding, S. T.	1941	Springs Rising Within the Bed of Utah Lake in Reports relating to Utah Lake—Chapter 3. Investigations of the Board of Canal Presidents of the Associated Canals. Salt Lake City, UT. Unpublished Report. 1941.			
3	Harding, William J.	1970	A Preliminary Report on the Algal Species Presently Found in Utah Lake			
3	Harding, William J.	1971	The Algae of Utah Lake, Part II			
3	Horton, A. H.	1903	Utah Lake Investigations. Third Annual Report of the Reclamation Service, 1903-4. U. S. Geological Survey, Department of the Interior. Washington, Government Printing Office. 1905.			
3	Hunt, C. B., H. D. Varnes, and H. E. Thomas.	1953	Lake Bonneville: Geology of Northern Utah Valley, Utah. U. S. Geological Survey Professional Paper 257-A. 1953.			

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
3	Javakul, A., J. Grimes, and S. R. Rushforth.	1980	Utah Lake phase 1 report #16: diatoms in sediment cores in Utah Lake, Utah, USA. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	Duplicate	Duplicate	
3	Javakul, A., J.A. Grimes, and S.R. Rushforth	1980	Diatoms in Sediment Cores in Utah Lake, Utah. U.S. Bureau of Reclamation WHAB Phase One Report #16. 1980	4	b	
3	Jensen, J. J.	1972	A Thematic Atlas of Utah Lake. Unpublished thesis, Department of Geography, Brigham Young University. 1972.			
3	Landom, K., C. J. Keleher, S. Rivera, and T. A. Crowl.	2014	Coupled ecosystem monitoring and biomanipulation in the shallow, eutrophic, Utah Lake. Final report to the June Sucker Recovery Implementation Program, Ecology Center and Watershed Sciences Department, Utah State University, Logan, Utah.	4	b	
3	Lovelace, Eric G.	1970	Utah Lake Water Budget Study, June 1970 through December 1971. Unpublished Master of Civil Engineering Project Report. Brigham Young University. Provo, UT 1972.			
3	Merritt, L. B., and A. W. Miller.	1981	Utah Lake Phase 1 Report #20: projected water quality conditions in Utah Lake and relationship to Central Utah Project. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	
3	R.L. Baskin, L.E. Spangler, W.F. Holmes.	1994	Physical characteristics and quality of water from selected springs and wells in the Lincoln Point-Bird Island area, Utah Lake. Utah Central Utah Water Conservancy District. 1994.			
3	Richards, D.C.	2017	Native Unionoida Surveys, Distribution, and Metapopulation Dynamics in the Jordan River-Utah Lake Drainage, UT	4	b	
3	Richards, D.C.	2018	Utah Lake Phytoplankton Taxonomic Update	4	b	
3	Rushforth, S. R., J. Grimes, and A. Javakul.	1980	Utah Lake Phase 1 Report #28: winter phytoplankton communities Goshen Bay Utah Lake, USA. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	
3	Rushforth, S. R., J. Grimes, and A. Javakul.	1981	Utah Lake Phase 1 Report #30: a study of phytoplankton along established permanent transects in Utah Lake, Utah, USA. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
3	Rushforth, S. R., J. Grimes, and A. Javakul.	1981	Utah Lake Phase 1 Report #33: site intensive study of algal floras of Utah Lake, Utah, USA. Eyring Research Institute, Inc., Brigham Young University, Provo, Utah.	4	b	
3	Rushforth, S.R. and L.E. Squires	1985	New Records and Comprehensive list of algae taxa of Utah Lake, Utah, USA	4	b	N/A
3	Shiozawa, D.K., J.R. Barnes, J.V. McArthur and R.Y. Oberndorfer	1981	Littoral Community Qualitative Study. U.S. Bureau of Reclamation WHAB Phase One Report #34. 1981			
3	Sonerholm, P. A.	1974	Normative Mineral Distributions of Utah Lake Sediments: a Statistical Analysis. Brigham Young University. Geology Studies 21(3):97-118.			
3	Strong, A.E.	1974	Remote Sensing of Algal Blooms by Aircraft and Satellite in Lake Erie and Utah Lake			
3	U.S. Bureau of Reclamation.	1961	The Chemical Quality of Utah Lake as a Result of Various Operation Assumptions. Unpublished report. 1961.			
3	U.S. Environmental Protection Agency.	1977	National Eutrophication Survey. Report on Utah Lake. Utah County, Utah, EPA Region VIII. Working Paper No. 861. 1977.			
3	USGS	1906	Underground Waters in the Valleys of Utah Lake and Jordan River, Utah. U.S. Geological Survey Water Supply Paper 157:81. 1906.			
3	Webb, M. A. H., and E. S. Cureton.	2010	Identification of cultural practices that induce stress during conservation propagation of the endangered June sucker, Chasmistes liorus. U.S. Fish and Wildlife Service, Bozeman Fish Technology Center.	N/A	N/A	
3	Whiting, M. C., J. D. Brotherson, and S. R. Rushforth.	1978	Environmental interaction in summer algal communities of Utah Lake. Great Basin Naturalist Vol. 38, No.1, 1978, pp. 31-41 . 1978			
3	Winget, Robert N. et al., J.R. Barnes, L.B. Merritt, S.R. Rushforth and D.K. Shiozawa	1982	Utah Lake Water Quality, Hydrology and Aquatic Biology Impact Analysis for the Irrigation and Drainage System - Central Utah Project: WHAB Phase II. U.S. Bureau of Reclamation. WHAB Phase Two Summary.	N/A	N/A	
4	Billman, E. J., and M. C. Belk.	2009	Growth and survival of juvenile June suckers in enclosures in Utah Lake: feasibility of modified cage culture for an endangered species. North American Journal of Aquaculture 71:281-286.	N/A	N/A	
4	Merritt letter to UDEQ(?)	2017	Utah Lake: A Few Considerations	1	b	

Priority	Author	Date	Title	Paper Categories	Charge Questions to Answer	Paper Secondary Categories
4	Richards, D.C.	2018	Relationships between Phytoplankton Richness and Diversity, Zooplankton Abundance, and cyanoHAB Dominance in Utah Lake, 2016	4	b	
4	Richards, D.C. and T.M. Miller,	2018	Recent Utah Lake Ecological Studies conducted by OreoHelix Consulting and the Wasatch Front Water Quality Council	4	b	